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AGE OF GULF BORDER SALT DEPOSITS[1]

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ABSTRACT

Normal marine deposits represent two independent but associated phenomena, clastic deposition and chemical salt precipitation. Widespread and evenly bedded marine clastic sediments owe their character to a combination of two factors: near-shore deposition coupled with shore migration. With regard to salt precipitation the salinity of the sea and various rivers is considered in connection with known saturation constants for different mineral salts. It is found that for any large portion of the sea to become saturated with sodium chloride, through evaporation, it is necessary that the enclosing basin become completely isolated from the open sea, also a condition probably essential to the formation of gypsum or anhydrite, but not essential to the precipitation of calcium carbonate. It therefore appears that the large marine salt basins of the geologic past must have been border basins, filled by sea transgression and isolated by sea retreat. Thus the salt should make up the middle series of sediments deposited during that marine cycle.

No large basin can be isolated from land drainage. Analysis of the effects of streams flowing from surrounding lands into desiccating marine basins shows that the normal precipitated rock sequence produced, as effected by shore recession under the influence of evaporation, is, from the bottom upward, limestone, gypsum and/or anhydrite, rock salt, anhydrite and/or gypsum, and limestone. The first three illustrate Usiglio's sequence; the latter two indicate the origin of the "cap rock," and provide one means whereby the age of the salt may be determined.

The dips of the strata of the Gulf Coastal Plain, generally south or southeast, decrease progressively up through the younger horizons. This is shown to be the normal result of repeated marine invasions. Salt occurrence is not uniform throughout the Coastal Plain. It is found at Smackover, in the Texas and Louisiana interior areas, and in the Gulf Coast proper. Several characters indicate the salt to be of different ages in the several areas of known occurrence, whence it follows that these different areas must represent different basins separated and bounded by pre-salt structures now deeply buried. These structures include the initial Sabine arch, with other structures south of Smackover and south of the Texas-Louisiana interior areas, respectively. Analysis of the overlying sediments shows all of these to be of pre-Comanche age.

The Mesozoic strata of the Gulf Border begin with the earliest Comanche, and they rest on a floor of Pennsylvanian or older rocks disrupted by the Ouachita and Appalachian orogenies. No intervening Permian, Triassic, or Jurassic strata are known.

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The lack of these as border facies precludes the possibility of a Permian, Triassic, or Jurassic age for the salt, and analysis of the Comanche sediments indicates the Smackover salt to be lowest Lower Comanche and the Texas-Louisiana interior salt to be Glen Rose.

On faunal, paleogeographic, climatic, and other bases the Gulf Coastal salt is indicated to be middle to late Upper Cretaceous. In this position it represents the Danian stage of the European section, which elsewhere in North America is lacking in a marine equivalent.

GENERAL INTRODUCTION

In the Louisiana and south and east Texas areas of the United States there exists a vast deposit of rock salt—sodium chloride. In exterior form this deposit of salt is known almost solely from the upper portions of vertical pillar- or stock-like masses, which present convincing evidence of having been forced in plastic or semi-plastic flowage by great pressure into the Cretaceous and Tertiary sediments in which they are now enclosed. The salt includes variable amounts of coarsely crystalline anhydrite, disseminated to the extent of about 2–12 per cent, in places more. Anhydrite also occurs, generally free from salt, in hard and dense "caps" above the salt pillars, though such caps are not uniformly present. Since low mounds have been observed in the terrane immediately overlying a few of the salt pillars, these structures have come to be known as "salt domes," more than one hundred of which thus far have been revealed in the area.

On account of the great similarities in their structure, composition, and geologic occurrence, and their geographic unity, the salt pillars are believed to indicate great masses of bedded salt underlying the area from which they were expelled. The sum of present evidence seems to indicate beyond question that the salt is of marine origin, that is, it is a very thick bed left by evaporation of sea water enclosed within a former marine basin, comparable with, but probably exceeding in size, the better known marine basins of Germany, Michigan, New York, West Texas, and elsewhere.

The age of the Gulf Border salt, the conditions under which it was formed, the cause of the doming effect, the origin of the cap rock, and many other associated questions long have been of geologic interest. These questions largely grow out of the great size of the basin of precipitation and thickness of the salt itself, characters that seem to have no counterpart in modern playas or shallow shore lagoonal phases of present-day marine saline deposition. Nowhere is there known an enclosed marine basin, 500–800 or more miles in width, a mile or two or more in depth, wherein the concentration and precipitation of salt might possibly be observed.

In this connection two facts seem to have escaped thorough dis-

cussion. 1. Even under conditions of unusual aridity the existence of such enormous cut-off "arms of the sea" wholly free of interior fresh-water drainage is quite improbable. 2. Fresh-water accession, either from inflowing rivers or from the open sea, may cause notable effects in the form and structure of the salt deposits, for the concentration and precipitation of salt is possible up to the point where the rate of fresh-water intake is practically equal to the rate of evaporation. Interpretations of existing saline stratigraphy, and experimental and theoretical studies in the evaporation of sea water, may not disregard the possibility or the character of such effects, especially as the size of the basin under consideration increases, though little information appears in the literature as to criteria for their recognition.

Incorporating these possibilities, the writer undertook a detailed analysis of sedimentational principles, after which the results were applied in an interpretation of the stratigraphy of the Gulf Coastal Plain. The analysis rests fundamentally on the principle of "initial dips"; this viewpoint was not intentionally recognized as a point of departure in the study, but it early assumed an important aspect and must be kept clearly in mind throughout the paper. Some of the interpretations that are presented, on the basis of initial dips, possess a disarming simplicity, for which the writer needs to offer no apology. In any given instance, if the stratigraphic structures can be explained adequately by simple sedimentational processes, such an interpretation is preferable to one involving crustal movement, especially where the dimensions of the affected area are small.

The great marine transgressions of geologic history indicate changes in the relative level of land and sea approaching hundreds of feet, perhaps several thousand. It seems more plausible and more probable to ascribe relative changes of this magnitude principally to crustal movement, elevation or depression, rather than to changes in the actual level of the sea, but in either case the effects are generally continental or greater in scale and are the same so far as initial dips are concerned. Accordingly, the marine transgressions and regressions are referred to, for the sake of simplicity, in this paper as risings and fallings of the sea.

The paper is divided into three parts. In Part I are discussed the processes and mechanics operative in the formation of marine stratified deposits, with the purpose in mind of determining the position the so-called "evaporites" should occupy in the sedimentary sequence of the marine cycle. In Part II the structural features and depositional history of the Gulf Coastal Plain are discussed. In Part III the principles studied in Parts I and II are utilized in an interpretation

of the regional history of the Gulf Border area, and the age of the salt.

I. FORMATION AND STRUCTURE OF DEEP BASIN MARINE DEPOSITS

INTRODUCTORY

Geologic history is decipherable chiefly through the sedimentary record of the sea. The record consists of those materials that have settled either from suspension as comminuted solids or by precipitation of dissolved salts to the floor of the former sea. Later deserted by the sea, they are left in the place of settlement for our inspection.

"Settling" implies gravitative control. Obvious for suspended comminuted solids, the same control exists over the dissolved salts, once they have been precipitated; obviously, however, gravity has no control over the place or cause of precipitation.

It is evident, furthermore, that a continuous supply of sedimentary material is a prerequisite to the generation of a continuous record. All others being negligible in comparison, only one possible source of supply exists for the sedimentary materials entering the sea, and that source is the land. Aside from sporadic contributions of submarine volcanoes and deposits of dust from the air, as well as the thin accumulations of planktonic tests, there exists only one locality where sediments may enter the sea, and that is along the shore.

CLASTIC CYCLE

Given, a basin containing water with admixtures of various suspended solids, and with no further supply, gravity will segregate vertically the suspended matter generally on the basis of degree of comminution. Thus the more coarse materials occur at the bottom, being those that settle most rapidly; from this layer there is a progressive decrease in grain size to the top of the final settlings. If the basin has not only its original supply of suspended matter but also a continued contribution through inflowing streams and from shore erosion, gravity will segregate the materials both vertically and horizontally, leaving the coarser materials at the shore to grade laterally (and vertically) into the progressively finer materials away from the shore. Aside from agitation of the water, the distance from the shore reached by any particle is dependent principally on its size and the slope of the floor beneath. Thus is derived the interpretation of shoreward approach when, in tracing a given geologic formation, its texture becomes coarser.

The mechanics of this process are most evident in lacustrine sedi-

mentation, or in picturing deposition in any body of still-standing water. They are more difficult to visualize, however, in connection with the regular and even-bedded sands and shales of marine deposition, extending without marked change in character or relation over areas of several states. For example, the Dakota sandstone, or the Pierre or the Eagle Ford shale, in their respective relations, are difficult to explain as deposits solely of still-standing seas. The same depositional mechanics were operative, but they were combined with migration of the shore, either transgression or recession. The marine strata of the geologic section are so generally of this type that still-standing seas appear to have been decidedly uncommon, nor can we consider the seas of the present to be different. Indeed it may be stated as a general principle that the only possible manner by which uniform deposition can be effected over wide areas is through deposition in a restricted zone combined with lateral movement of that depositional zone.

It may be noted that, with shore migration, the distance from the shore that deposition is effected does not change, other things being equal, and that the waters beyond the zone of deposition of the finest clastics are free from clastic material. Thus, with a transgressing sea, as the clastic depositional zones proceed up the slope with the advancing shore, the clear waters beyond the outer and finer zone are ever deepening over the floor of mud that has just been laid, and no further deposition of clastic material possibly can take place above it. At last the inundation reaches a maximum, and then begins the slow retreat. The outer and finer zone is the first to be deposited before the retreating shore upon the floor laid in transgression; retreating mud comes back first upon transgressing mud. With possible identity of material, the contact between the two may not be distinguishable; the shale thus formed may appear to be a single stratum and to constitute a continuous record, yet within there obviously is a hiatus whose time value at any specified point depends on the distance of the point from the shore line of reversal (the shore line at maximum inundation) and the duration of the submergence. For an illustration of a break or gap within a shale, probably with this origin, see page 1246.

The clastic cycle thus outlined is illustrated by Figures 1 and 2, with the latter somewhat the more diagrammatic. Almost self-explanatory, suffice it to call attention to three features. 1. Note in Figure 1 the tendency to increased thickness in the retreatal series. In transgression a more or less uniform distribution of material takes place over the widening area of the land transgressed. Great thicknesses thus are not impossible, but they are unlikely. With retreat, in

contrast, the vacated floor of unconsolidated sediments is subjected in enlarging areas to continually increasing erosional activity. The products are returned again and again into the gradually constricting shore zone, so that great thicknesses and more or less irregular bedding are to be expected. 2. The last retreatal clastics to be deposited are the coarse materials of the shore zone, and these very generally are red beds. Constantly reworked, with repeated alternations of sub-

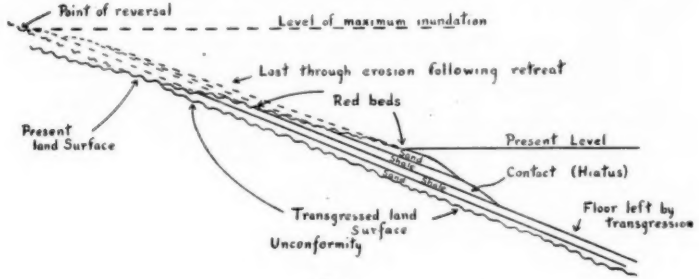


FIG. 1.

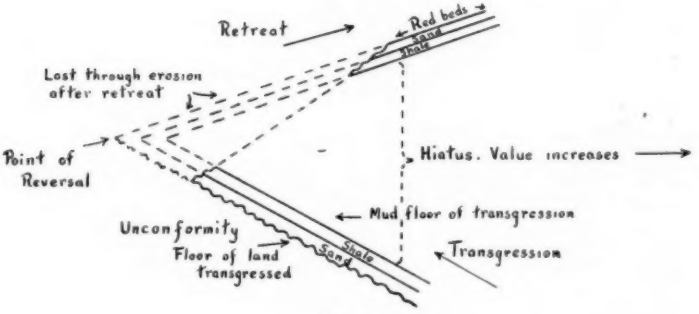


FIG. 2.

mergence and sub-aerial exposure, they are subjected to the optimum conditions for complete oxidation. Warm and semi-arid climates favor such complete oxidation, but they are not essential. 3. Note the decrease in initial or depositional dip in the formations as the cycle proceeds, so that as a whole the cycle results in a thin wedge-shaped section, a feature illustrated by Grabau.[3] The change in a single cycle may be slight. If, however, there is a repetition of cycles in the same orientation, the piling of the wedges above one another produces a

[3] A. W. Grabau, *A Textbook of Geology*, Part I, p. 615. D. C. Heath and Company, New York (1920).

marked change in attitude. The great importance of this factor in Gulf Coast geology is brought out in Parts II and III.

Since the basis of all the reasoning and interpretations in this paper is (1) that of initial dips and (2) that of crustal deformation where initial dips are precluded, it is pertinent at this time to understand the possible extent to which dips in inclined marine strata may be regarded as initial. The fact is obvious that a marine transgression indicates the water relatively to be passing upward over a sloping surface. Since the clastic sediments are deposited in a near-shore zone, and regular strata formed by migration of that zone, it also is obvious that such clastic formations must have possessed some initial dip, and that any present inclined attitude should not be attributed to crustal uplift or other movement without prior careful consideration of the possible extent to which such inclination may be an initial attitude.

It is safe to say that an initial dip cannot exceed the "angle of rest" for a given clastic material, unconsolidated, in water. This value varies according to the size of the individual particles, being large for coarse conglomerates and small for the finer silts and clays. For a sand of average-size grains the angle of rest is approximately 6° in still water. With agitation of the water it may be less, but under ideal conditions it may be safely assumed that a marine sandstone could have possessed an initial dip approaching 6°.

A slope of 6° equals 555 feet per mile. Due to wave, current, and tidal movement it is improbable that any marine sandstone has been deposited with an initial dip of such magnitude, but this possible value is so great that probably very few marine sandstones or shales have been formed without an initial dip worthy of careful consideration. Hence, in all of the following discussion, observed dips are treated as initial unless conclusive contrary evidence is present.

PRECIPITATED SALT CYCLE

1. *General.*—In considering precipitates from dissolved salts, the processes become more complicated, but are not changed greatly in character. As with clastic sediments, the only possible ultimate source from which salts can enter the sea is the land, and the only possible gateway is through the rivers and underground drainage along the shore. Once these fresh solutions have entered the sea, distribution of the dissolved salts is a function of chemical diffusion, which is exceedingly slow, even when assisted by wave and current agitation.

2. *Means of precipitation.*—Dissolved salts can take no part in the sedimentary record until they are precipitated. The means of precipitation of those salts most common in the sedimentary sequence

is through evaporation of the solvent, with the eventual attainment of saturation concentrations, if for the time being the possible influence of organisms in the precipitation of calcium carbonate may be disregarded.

3. *Evaporites.*—In a strict sense all salts in the sea may be considered as evaporites, for any salt, if present in excess of its particular saturation value, under the given conditions, will precipitate. The term most commonly designates sodium chloride and calcium sulphate, but, since it also is a mineral salt, calcium carbonate is subject to exactly the same physico-chemical laws as determine the action of any other mineral salt. In this relation it has equal demand with calcium sulphate and sodium chloride for consideration as an evaporite.

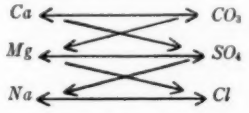
4. *Order of precipitation of dissolved salts.*—The classic experiments of Usiglio in the evaporation of sea water are summarized by Clarke.[4] With evaporation calcium carbonate was the first salt to appear; its precipitation slightly overlapped that of gypsum, the second salt, which, in turn, considerably overlapped that of sodium chloride. The latter did not appear until 0.9 of the water had evaporated. The stratigraphic succession, experimentally, thus becomes (1) a layer of calcium carbonate, (2) a layer of calcium sulphate containing some carbonate, grading upward into (3) sodium chloride containing minor amounts of each of the other two salts. The thickness of each layer depends on the absolute concentration in the original solution for that particular salt; hence, for ordinary sea water the thicknesses of the several layers will increase in the order named. The order of precipitation, in contrast, obviously is a function not of absolute concentration, but of the percentage saturation for each salt in the original solution; in other words, Usiglio's experiments show that sea water is very nearly saturated with calcium carbonate, less so with calcium sulphate, and very much less so with sodium chloride, though absolute concentrations are the reverse.

On the other hand, Usiglio's experiments fulfill only in part, and do not duplicate entirely, marine evaporational processes as they take place in nature, for in nature no sea basin, however large or restricted, is free from land drainage, and the basins where this is a negligible factor are very rare. The effects of additions during evaporation thus become more or less important factors in natural processes. Furthermore, in many of the important marine salt deposits calcium sulphate followed by calcium carbonate has been noted also above the salt, a sequence again observed in the "cap rock" above the salt pillars of

[4] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Survey Bull. 770* (1924), pp. 219–21.

the Gulf Coast. For examples of this sequence, see page 1243 *et seq.* Usiglio's experiments throw but partial light on this succession. It may be noted, however, that this is exactly the reverse of the order of precipitation that he observed. In this respect there appears to have been operative a process of decreasing rather than increasing concentration—a progressive freshening effect. In other words, a brine saturated with sodium chloride through the evaporation of sea water might be freshened with respect to sodium chloride without affecting the precipitation of calcium sulphate or calcium carbonate, provided the freshening solution is saturated with each of the latter two salts. Similarly, the freshening solution might be saturated only with calcium carbonate, in which case precipitation of the other two salts would be inhibited.

5. *Percentage saturations for various salts in river and ocean waters.*—Clarke presents many ionic analyses of river and ocean waters. In the interest of brevity and continuity of thought it is unnecessary for them to be repeated here, but if they are calculated to probable salts according to relative insolubility, namely,



and if the resulting salt concentrations are compared with established saturation constants for the respective salts, two conclusions appear to be substantially supported. 1. Both river and ocean waters are essentially saturated with calcium carbonate. 2. The percentage saturations of salts, in both river and ocean waters, decrease in the same order from calcium carbonate through calcium sulphate to least percentage saturation for sodium chloride. For example, four such calculations yield the following information (Table I).

TABLE I

PERCENTAGE SATURATIONS FOR VARIOUS WATERS

Salt	*Mississippi River*	*Red River*	*Brazos River*	*Ocean*
$CaCO_3$	142.	200.	224.	335.
$CaSO_4$	Trace	.52	14.0	67.0
$NaCl$	.004	.057	.15	7.8

The solubility of calcium carbonate has been studied thoroughly by Johnston and Williamson.[5] The high percentage saturations (Table

[5] John Johnston and E. D. Williamson, "The Rôle of Inorganic Agencies in the Deposition of Calcium Carbonate," *Jour. Geol.*, Vol. 24 (1916), pp. 729–50.

I) for this salt arise through inability to estimate the effect of other dissolved salts on the solubility of the carbonate, and more so, perhaps, through inability to determine the exact way in which the ions expressed in the analyses are actually combined.

The rivers cited in Table I were chosen because they are important contributors to the Gulf of Mexico. Incidentally, note the character of the waters of the Brazos and Red rivers as contrasted with those of the Mississippi. These two rivers drain across the Permian basin, whose influence is markedly apparent, and probably has long been effective, in the gypsum and salt concentrations in the waters of the present rivers.

6. *Ease of precipitation.*—In the light of the foregoing considerations it is possible to estimate the ease with which precipitation of any salt in the sea may be effected. It is evident that a very slight variation in physical conditions is sufficient to cause or to terminate precipitation of calcium carbonate, while highly specific conditions are demanded for the attainment of saturation concentrations for sodium chloride (35.7 per cent at 0°C.), with intermediate requirements for the precipitation of calcium sulphate. If the open seas of to-day should start creeping up over the coastal areas, increased temperature and quickened evaporation over the shallow shores would be sufficient to cause calcium carbonate to precipitate. Entrance of the sea into restricted basins of course would favor such precipitation; considerable restriction probably would be essential to the precipitation of calcium sulphate, though for sodium chloride it seems that a basin completely isolated from the open sea is demanded.

7. *Meaning of isolation.*—Isolation as employed here signifies the complete prevention of egress of the solution within the basin. This does not preclude, however, the supposition that a basin might be possible with a water level lower than that of the external sea, and that over a shallow eustatic bar a continuous or intermittent supply of water, less in amount than that lost through evaporation, might enter the basin. These are the relations that have been represented as accounting for the great volume of salts generally found in the large marine deposits.

Such conditions probably could not persist through any geologically great length of time; at best they would be extraordinary. No basin, however, can be isolated from land drainage. It is commonly held, therefore, that the climate prevailing at the time of salt formation must have been very warm and arid, for under such assumptions the rate of evaporation is high and the rate of fresh water contribution is low.

8. *Comparison of rate of evaporation with rate of flow of some modern rivers.*—It seems reasonable to believe that by a fair approximation of variables significantly dependable figures should be obtained concerning rates of evaporation from open bodies of water under conditions prevailing in nature. Substituting the following values in Rohwer's[6] formula, the rate of evaporation is found to be 1.65 pounds per square foot per 24 hours over the surface of a brine saturated with sodium chloride.

Wind velocity	10 miles per hour
Relative humidity	25 per cent
Air temperature	100° F.
Brine temperature	80° F.

These values were chosen as representing those conditions considered likely to have prevailed over the Gulf of Mexico at the time of salt formation. They are based on the following considerations, and, while admittedly assumptions, they are believed to be conservative.

The brine temperature is the most reliable factor, the value assigned being chosen in accordance with the known physico-chemical relations of calcium sulphate and sodium chloride in aqueous solution. In an aqueous solution saturated with both sodium chloride and calcium sulphate the inversion temperature between gypsum and anhydrite has its lowest value at about 77° F.,[7] anhydrite forming only above that temperature, and the temperature of inversion rises with decrease in sodium chloride concentration. Since anhydrite is the original form developed abundantly in the Gulf Border deposits, 80° F. represents about the lowest possible brine temperature that may be assumed.

Though this as a brine temperature appears to be conservative, as an average or prevailing temperature for modern seas it is high. In order to maintain such a brine temperature, which may have been even higher, it is evident that the mean atmospheric temperature must have been considerably higher than that prevailing to-day. In the southwestern deserts of the United States day-time temperatures well above 100°F. are not uncommon, though night temperatures generally are considerably lower. The Gulf of Mexico, however, is appreciably farther south, and over the seas diurnal fluctuations are less marked. For these reasons it is felt that 100°F. as an average atmospheric temperature is a conservative value.

[6] Carl Rohwer, *U. S. Dept. Agr. Tech. Bull. 271* (1931), p. 66.

[7] Oliver Bowles and Marie Farnsworth, "Physical Chemistry of the Calcium Sulphates and Gypsum Reserves," *Econ. Geol.*, Vol. 20 (1925), pp. 738–45.

The other two factors are less certain. Average relative humidity over modern deserts may range around 25 per cent. The function of wind velocity represents the rate of removal of saturated air and its replacement by air 25 per cent saturated. With small bodies of water —artificial tanks, for example—both of these functions may be determined with an accuracy that decreases as the size of the basin increases. Averaging or prevailing wind velocities in the southwest to-day probably exceed 10 miles per hour. For these reasons it is felt that the latter value and 25 per cent humidity are suitable for dependable calculations.

What the outer boundaries of the Gulf of Mexico may have been at the time of salt formation may not be determinable. There is no great evidence that they were far different from those of to-day, except along the eastern margin in the vicinity of the "Floridian Plateau." Certainly this enclosed basin had vast proportions. The present area of the gulf is about 7.35×10^5 square miles. Using half of this value, since in large basins evaporation effects must be greatly accentuated nearer to the bordering lands, with an evaporation rate of 1.65 pounds per square foot per 24 hours, the total evaporation rate becomes 3.1×10^6 cubic feet per second (second feet).

This may be compared with the present rates of discharge of some important rivers entering the gulf. According to measurements recorded in various Water Supply Papers of the United States Geological Survey, the combined flow of the following rivers—Red, Brazos, Colorado, Trinity, Neches, Sabine, and Rio Grande—aggregates approximately 6×10^4 second feet. By comparison the rate of evaporation over one half of the gulf area computed above is slightly over 50 times this rate of contribution.

Figures on the average rate of flow of the Mississippi do not seem to be readily available. More than 1,000,000 second feet have been recorded at Vicksburg at flood stage, with a minimum of 65,000 second feet recorded at other times. It is probable that 500,000 second feet exceeds the mean annual flow by a considerable amount, and still the calculated rate of evaporation is about 7 times this figure.

Though it may be argued that accurate estimation of the processes taking place on the scale exhibited by nature is an impossibility, and that all of the figures derived here depend on many assumptions, still the conclusion seems more or less strongly supported that concentration and precipitation of sodium chloride and associated salts in large marine basins can take place in distinctly semi-arid climates.

The same conclusion may be derived from other considerations. The total present run-off into the sea and the total evaporation from

the sea are approximately equal, taking the earth as a whole. If any sizable border basin should be isolated from the sea, the prevailing climate in that locality might not be changed, necessarily, but the local balance between evaporation and run-off probably would be disturbed in one direction or the other. If the evaporation to run-off ratio should be slightly increased, there will result a corresponding decrease in water volume in the isolated basin and an increase in salt concentration. With continued decrease in surface area the evaporation to run-off ratio gradually decreases to unity, where it will remain as long as similar external conditions persist. Considerable thicknesses of sodium chloride thus might be built up, and even the rarer salts might appear. The more arid the local climate, the less time will be required to bring about this concentration, but that a strictly arid climate is not essential has already been shown.

9. *Adequacy of salt supply.*—Moreover, it seems probable that rain wash over the wide expanse of bordering sea-soaked lands just vacated by the retreating sea may be largely the cause for the mass of salts accumulated in the basin. For example, Harris[8] writes, concerning the Kansas and Oklahoma areas, that "salt occurs in Kansas . . . as surface deposits in salt marshes or plains derived from brine in Cretaceous shales."

Let there be assumed a mass of rock salt 100×400 miles in area, averaging 2,500 feet in thickness, dimensions in some measure approximating those of the salt deposit in the great Gulf basin. With its present salinity and rate of flow, Brazos River would contribute this amount of salt in approximately 140,000 years. To contribute the same amount, the Mississippi, with its present salinity and a rate of flow of 300,000 second feet, would require approximately 233,000 years. Neither of these periods is of unreasonable duration. Yet the calculated rate of evaporation is considerably in excess of the rates of flow of both rivers combined, and the salt contributions of the two rivers, combined with those of other important rivers entering the Gulf, materially decrease the figure of 140,000 years found for the Brazos alone.

10. *Freshening effect.*—In the preceding paragraphs it has been attempted to show that the great deep-basin evaporite deposits owe their magnitude to the contributions of inflowing rivers to an unsuspected extent. If this is true, the effect of inflowing streams on the form and structure of the salt deposits should become evident in some way. This phenomenon may be called the freshening effect. It is sus-

[8] G. D. Harris, "Rock Salt," *Louisiana Geol. Survey Bull.* 7 (1907), p. 94.

ceptible to mathematical treatment, but the many variables involved are difficult to estimate and a qualitative analysis is comparatively simple and is sufficient for present purposes.

Imagine a closed basin, containing a solution of a single salt and receiving no drainage, to be concentrating through evaporation. Eventually the saturation concentration is reached, and with further evaporation the salt precipitates. Then imagine a stream of pure water to be entering the solution, less in total contribution than the loss through evaporation over the surface in the basin. It is evident that salt precipitation will be zero at the mouth of the river, and that the zone of maximum accumulation of the salt will be shifted away from the shore near the river. Alter the case to that of a river, now saturated with the same salt, entering the saturated solution in the basin with excess evaporation as before. It appears that the effect of the river will be to more or less maintain the level of the solution in the basin; it can have no effect on the form of the deposit or the place of precipitation within the basin. Next, if the salt is present in the river in less than the saturation concentration, it is evident that some freshening will be felt at the river's mouth, but not as far out as with a still lower salt concentration. According to the percentage saturation of the river, then, the freshening effect should be expected to inhibit precipitation in a zone moving nearer to, or away from, the shore as the percentage saturation of the river is increased or decreased.

Next, imagine a portion of the sea to become isolated and evaporated to sodium chloride saturation. It will then be saturated also with calcium sulphate and calcium carbonate, and these three salts will continue to precipitate together. Then imagine a normal river to be emptying into the basin. With a high percentage saturation for calcium carbonate, the freshening effect for this salt is very slight, and it will continue to precipitate relatively near the shore. For calcium sulphate the percentage saturation in the river is considerably less, so the freshening effect will be felt farther out. For sodium chloride, precipitation will be inhibited yet farther from the shore, since its usual percentage saturation in river waters is very much less than for either of the other two salts.

As an illustration of the freshening effect, mention may be made of the distribution of the salts in the Dead Sea, due to the influence of Jordan River. Also, Harris[9] in describing the Salinas de Cordoba in Argentina writes, "In general the gypsum is deposited near the margins and the salt toward the center of the basin."

[9] G. D. Harris, *op. cit.*, p. 129.

11. *Freshening effect and migrating shore.*—Concentration of a salt in a marine basin through evaporation implies a gradual retreat of the shore; hence, the freshening effect must be considered in this relation.

It has been shown that sodium chloride saturation can be obtained only in a closed or isolated basin. Thus sodium chloride never can form in a transgressing sea, for a closed basin cannot remain long in the face of an advancing sea. Calcium sulphate perhaps may form, but transgressive conditions in general must be unfavorable to its precipitation. On the other hand, it has been shown that very slight alterations of physical conditions may cause precipitation of calcium carbonate, so that transgressive precipitation of this salt easily is possible. The transgressive seas of the past, as witnessed by the known geologic section, laid down thick and widespread strata of limestone. Regressive seas, however, are essential to the isolation of border basins and the precipitation of sodium chloride therein, and they are almost if not quite essential to the precipitation of calcium sulphate. Certainly they favor the precipitation of any salt, even though they may not be essential.

Given, then, a transgressing sea, in which calcium carbonate is precipitating. The freshening principle states that precipitation of this salt generally begins not far off shore. With shore advance the distance to this zone is not changed, other factors remaining equal. Hence, with transgression a layer of calcium carbonate is deposited more or less uniformly over the surface of the land transgressed, or, more accurately, above the clastics of shore deposition.

After reaching the maximum inundation the slow retreat begins. With the return of the freshened landward zone, precipitation of limestone eventually ceases, and over the whole sequence the final shales and sands of shore deposition are laid, completing the record of the cycle.

If, however, the retreat is into a closed basin, under the influence of evaporation, other salts begin to appear at successive intervals, first calcium sulphate and next sodium chloride. The freshening principle shows that precipitation of these salts is inhibited considerably farther out than for calcium carbonate. Hence, with retreat of the enclosed sea under evaporation, and formation of these salts, calcium sulphate followed by sodium chloride must precipitate above the calcium carbonate according to Usiglio's sequence, but, as the shore recedes, the sodium chloride grades upward into calcium sulphate and eventually the retreatal limestone lays down a stratum of calcium carbonate above the whole, representing the freshening influence.

This sequence is illustrated in Figure 3, in which the dips shown necessarily are exaggerated. Since the figure illustrates a precipitate sequence only, it should be said that later the shoreward clastics also come down over the limestone, first the shales and then the sands, to complete the cycle.

12. *Salt accessions over shallow marine bar.*—It has been shown possible in the preceding discussion for the salt mass to have been derived from the initial volume of sea water with later accessions solely from inflowing rivers. No mention has been made of possible further

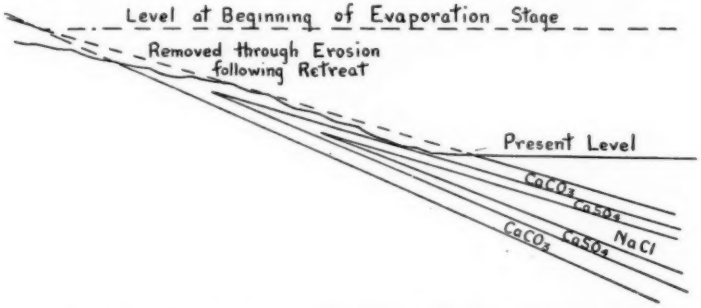


FIG. 3.—Ideal cross section of a marine basin, in which concentration of salts is taking place concomitantly with continuous inflow of fresh waters around the shores. Usiglio's sequence at base of salt, freshening sequence above salt.

contributions from the sea over a shallow eustatic bar. It may be noted here, that, though river contributions are capable of furnishing the whole volume of salt, and are responsible for the development of the "cap" sequence, the same effects can be produced by inflows from the sea. The percentage saturations of calcium carbonate, calcium sulphate, and sodium chloride in sea water are greater in magnitude than in fresh waters, but they exist in sea water about in the same relative values as in fresh waters. It follows, therefore, that marine contributions will develop the same vertical sequence, through the freshening effect, as will fresh inflowing streams, provided the rate of addition is less than the rate of evaporation, so that the level of the solution in the concentrating basin gradually subsides.

13. *Perfection of development of freshening (or cap) sequence.*—The precipitation of sodium chloride in marine basins demands complete isolation of the basin from the open sea, in the sense previously explained, and withdrawal of the excess water by evaporation through the salt saturation stage. These conditions do not preclude the addi-

tion of water during evaporation, either from the open sea or from inflowing streams, except that the rate of such addition must not exceed the rate of loss through evaporation. When the rate of loss is exceeded the basin must gradually fill and overflow, and salt formation can not take place.

It may be seen, however, that, even with inflowing streams, evaporation can bring about salt saturation up to the point where the refreshing waters enter at a rate almost if not quite equal to the rate of evaporation, in which case the factor of time becomes of increasing importance. It is obvious that with a given basin the time necessary to bring about salt saturation will be least when the original volume of water only is involved, and as the rate of entry of refreshing waters increases the time also increases.

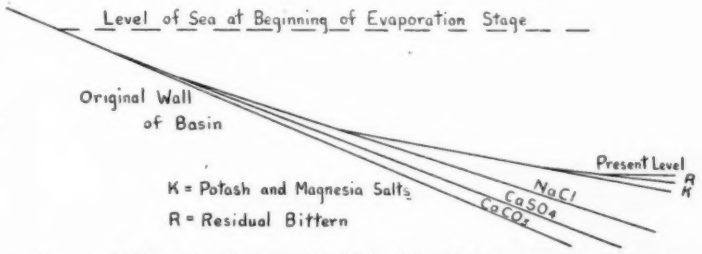


FIG. 4.—Ideal cross section of marine basin, almost dried up through evaporation, without receiving any fresh water, from any source, during evaporation; hence, no zoning can take place except according to Usiglio's sequence.

Thus there are two genetic extremes, (1) desiccating basins receiving extraneously not a drop of refreshing water, and (2) desiccating basins receiving fresh water at a rate equal to the rate of evaporation, genetic extremes which encompass the conditions of formation of every major marine salt deposit. Under the first extreme no freshening (cap) sequence is possible, and the ultimate salt deposit can show zoning, lateral and vertical, only according to Usiglio's sequence, as illustrated in Figure 4. But if there is any influx of freshening water, at a rate less than the rate of evaporation, the level of the solution in the desiccating basin must go down, and the freshening sequence must form above the salt, with Usiglio's sequence at the base of the salt. It is improbable that any marine salt deposit of the first magnitude ever has formed under the strict conditions of either extreme. As the rate of fresh water inflow decreases, the perfection of development of the freshening sequence also decreases; it is possible, too, that in some cases the refreshing influences were highly localized within the basin,

so that, all in all, many variations and complications may be expected. The diagram presented in Figure 3 is that of an ideal case, but all marine salt formations must approach this ideal as the size of the enclosed basin increases, and as the aridity of the then prevailing climate decreases. Reference will be made to this point in Part III (pp. 1285–86).

The existence of calcium sulphate beds above sodium chloride horizons has been noted in many instances, a sequence which the writer ascribes to the freshening influence as the enclosed sea recedes under evaporation. A chemical theory was proposed by Lane[10] to account for this superposition as observed in the Michigan deposits. A very instructive section of the German Permian deposits, near the Thuringerwald, is that by Dietz,[11] compiled from the records of 139 deep borings. A representative illustration is his No. 125, as follows.

Depth (*Meters*)	*Formation*	
205.2	Buntsandstein	
230.8	Bunter Ton (Brockelschiefer und Obere Zechsteinletten)	
254.0	Plattendolomit	
286.2	Rote Letten	Oberer Zechstein
299.5	Anhydrit	
342.8	Salzton mit Anhydritschichten	
477.5	Steinsalz	Mittlerer und Untere Zechstein
480.6	Anhydrit	
492.0	Zechstein	
496.4	Weissliegendes mit Konglomeraten	Rotliegendes
622.0	Rotliegendes mit Konglomeraten	

The Permian salt section at Sperenberg shows the same superposition.[12]

Formation	*Thickness* (*Feet*)
Detrital material	2.06
Bluish gray gypsum	279.48
Nearly white anhydrite with gypsum	5.14
Pure anhydrite	1.96
Anhydrite with rock salt	2.62
Pure transparent rock salt	3,879.06
(Boring ended in salt)	

Farther in the basin, within the area of occurrence of potassium salts, around Stassfurt, the section is confused by early tectonic movement. The massive "older salt" bed, regionally present, is covered by

[10] A. C. Lane, *10th Ann. Rept., State Geologist*, Lansing, Michigan (1908), p. 62.

[11] C. Dietz, "Die Salzlagerstatte des Werra-Kaligebietes," *Archiv für Lagerstättenforschung*, Heft 40. Preussischen Geologischen Landesanstalt, Berlin (1924), p. 124 and Tafel I.

[12] *Eng. and Min. Jour.* (1884), quoted by G. D. Harris, "Rock Salt," *Louisiana Geol. Survey Bull.* 7 (1907), p. 144.

a thick anhydrite series, which, in local areas, is succeeded by the "younger salt," though this, too, is succeeded by anhydrite or gypsum, and the whole is covered by heavy red clays and shales which the writer interprets as the end of the desiccation cycle. Gray salt clay intervenes between the older salt and the main anhydrite. Contrary to the usual interpretation, the writer believes this can not be accepted as representing the closing clastic phase of the cycle, for several reasons: (1) it is far too thin (25 feet) and uniform in comparison with the magnitude of the desiccating basin; (2) it is gray in color, whereas closing clastic sediments generally are red; (3) it is composed partly of precipitated magnesia, which is difficult to associate with shoreward deposition; (4) it is coterminous with the potash-bearing areas within the basin and absent from the bordering areas (see the Sperenberg section), where it should be well represented if a clastic border phase.

Nor does the writer believe the younger rock salt and underlying anhydrite above the gray salt clay can represent a new cycle of marine flooding and evaporation. The local development and comparative thinness of the younger salt (125–400 feet as compared with 500–3,000 feet of the older salt) are not in harmony with such an assumption. On the contrary, to the writer the evidence indicates tectonic disturbance to have occurred prior to complete desiccation of the large older salt basin, causing changes in freshening inflows, and subsidence in local areas wherein salt precipitation might be resumed locally for a brief interval before the end of the great desiccation cycle. In considering this view, note the maps and sections of Fulda,[13] the Prussian Geological Survey,[14] and others.

Two other sections, quoted by Harris,[15] are of interest, those at Heilbronn and Wilhelmsgluck, in Wurtemburg, where the salt is in the Middle Triassic.

	Thickness (Feet)
HEILBRONN	
Principal dolomite region	36
Principal anhydrite region	101
Intermediate formation [mixed salt and anhydrite.—L.S.B.]	26
Rock salt	131
Basal anhydrite, approx.	19
WILHELMSGLUCK	
Principal dolomite region	26
Principal anhydrite region	95
Intermediate formation	26
Rock salt	16–39
Ground dolomite	29

[13] *Das Kali*, II Teil, verfasst von Ernst Fulda. Stuttgart (1928).

[14] *Uebersichtskarte der Deutschen Kalisalz- und Erdölvorkommen*. Scale, 1:450,000. Preuss. Geol. Landesanstalt, Berlin (1924).

[15] G. D. Harris, *op. cit.*, p. 155.

CLASTIC AND PRECIPITATED SALT CYCLES COMBINED

Thus there have been outlined two types of marine cycle, the clastic cycle and the precipitated salt cycle. In nature these are concomitant, though functionally they are independent of one another. As a rule it has happened that the zone of limestone precipitation stood somewhat offshore, beyond the zone of silt-shale settlement. Departures, however, are not uncommon; for example, if local conditions permit but slight freshening effect, limestone will be precipitated plentifully in the shale zone, and marls will result. This has been illustrated by Thoulet,[16] who found calcium carbonate films precipitating on the silt particles in the Gulf of Lyons at the mouth of the Rhone. Precipitation of the carbonate chiefly in the sandy zone will give rise to calcareous sands or to sandy limestones. Temporary or local disturbances of the freshening ratio by river floods, drainage capture, inter-sea connections, et cetera, cause the variations in normal character and sequence of the formations, such as limestone lenses in a sand or shale, shaly layers in a limestone, or, in unusual occurrences, the absence of a middle limestone formation between a transgressive and retreatal shale sequence. The latter case seems to be excellently illustrated in the gap in the Eagle Ford formation in central Texas, as described by Stephenson.[17] The upper and lower parts of the formation are found at Austin, Texas, with the gap between the two gradually closing northward as far as the vicinity of Waco and Dallas where the intermediate section appears. Since this is the direction of all of the transgressions of the Mesozoic era in the gulf area, the gap appears to represent a minor advance and retreat of the sea. Remembering that the Cretaceous sea established connection with the Arctic Ocean at the close of, or shortly following, the Washita stage, it seems reasonable to infer that the absence of the middle limestone, which normally should be expected to occupy the gap in the shale, is due to this temporary influx of considerably cooler water from the north.

The writer is inclined to ascribe the faunal change at the end of the Comanche also to this influence. The stratigraphic relations between the Comanche and Gulf series are such as to make it difficult to believe that a mighty erosional unconformity exists between the two series, and that evolutionary progress alone beyond the bounds of the unconformity is responsible. Some more abnormal factor must have been involved.

[16] John Johnston and E. D. Williamson, *op. cit.*

[17] L. W. Stephenson, "Unconformities in Upper Cretaceous Series of Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), pp. 1323–34.

A complete marine cycle thus is shown ideally in either of the following sequences from the bottom upward.

USUAL SEDIMENTARY SEQUENCE ILLUSTRATING MARINE CYCLE. NO CLOSED BASIN INVOLVED

Retreat	Sand, Shale	Red beds
	Limestone	
Transgression	Shale	
	Basal sand, commonly lignitiferous	

OCCASIONAL MARINE SEDIMENTARY SEQUENCE, DEVELOPED BY FRESHENING INFLUENCE DURING EVAPORATIONAL RETREAT INTO CLOSED DEEP BASIN

Retreat	Sand, Shale	Red beds	
	Limestone		
	Anhydrite	Cap Rock	Top of Salt series, freshening effect
	Salt		
	Gypsum and/or anhydrite		Base of Salt series, Usiglio's sequence
Transgression	Limestone		
	Shale		
	Basal sand, commonly lignitiferous		

In the second sequence the evaporites have been indented to represent the off-lap caused by contemporaneous salt concentration and evaporational shore retreat within the closed basin. Any one of the salts should be free of any other salt on its right, but should include disseminated precipitates of all other salts on its left. The ratios of absolute concentrations of these three salts in sea water are such that sodium chloride greatly predominates in volume over the other two, and may appear as relatively pure salt. Likewise calcium sulphate predominates over calcium carbonate, thus masking disseminated carbonate. As has been pointed out in an earlier paper,[18] syngenetic rhombs of carbonate are of universal occurrence in cap rock.

CONCLUSIONS DERIVED FROM PRECEDING STUDY OF MARINE CYCLE

1. *Stratigraphic position of evaporite.*—In the foregoing discussion it is seen that the so-called "evaporites," in so far as these are of deep marine formation, make up the "middle" and grade into the "upper" series of the cyclical sequence. This is not an entirely novel discovery, having been stated some years ago by Grabau, according to Barton and others.[19] Whatever merit in this regard the present paper may possess lies in the suggestion of a reasonable series of physico-chemical processes by which such a stratigraphic sequence might be established.

[18] Levi S. Brown, "Cap-Rock Petrography," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 5 (May, 1931), pp. 509–31.

[19] Personal communication, September 29, 1933.

Again, the middle position of limestone within the shales of the usual marine sequence is an illustration of precisely the same principle, only employing different materials.

A few examples may be quoted. The salt in Michigan, Ohio, and New York occurs in the Salina, Middle Silurian. In Germany the salt is in the Zechstein, with other deposits in the Muschelkalk and in the Keuper. At Saltville, Virginia, the salt is in the lower part of the Greenbrier limestone, lower Upper Mississippian. Getzendaner[20] writes that "near Eagle Pass the Rycade Oil Corporation's Chittim No. 2 disclosed 20 feet of coarsely crystalline rock salt at the top of the Edwards or at the base of the Georgetown," which also is a middle position, for the Edwards is a transgressive and the Georgetown a regressive limestone.

In the middle of the Glen Rose limestone of north-central Louisiana and near-by localities in Arkansas and Texas occurs a section with identically the same relations. Five hundred feet of lower Glen Rose limestone are succeeded by about 450 feet of massive anhydrite, and this by about 400 feet of upper Glen Rose limestone. Characteristic faunas are found in both limestones, though in the Homer field the fauna has been observed to be of dwarfed fossils.[21] It is evident that the lower limestone bed was formed in a transgressing sea, while the anhydrite and upper limestone were deposited as the sea receded.

A thinner bed of anhydrite occurs in the Glen Rose as revealed by a well (McAngus No. 1) in eastern Travis County, Texas.[22] It is here much thinner because the locality is nearer the shore line of reversal of the Glen Rose cycle. Celestite,[23] another important evaporite, is widely developed in the Glen Rose of central Texas, and the writer previously has described its syngenetic development. It is found to some extent associated with gypsum nodules, though in general it occurs farther inland than the gypsum. Where found, it is in the form of coarsely crystalline nodules, generally 2–6 inches in diameter, though some are 2–3 feet. Its common placement is in pockets in the upper Glen Rose. In Williamson County, along San Gabriel River, it is found abundantly at the top of the Glen Rose, at the contact with

[20] F. M. Getzendaner, "Geologic Section of the Rio Grande Embayment, Texas, and Implied History," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 11 (November, 1930), pp. 1425–37.

[21] E. H. Sellards, W. S. Adkins, and F. B. Plummer, "The Geology of Texas," Vol. I, *Univ. Texas Bull. 3232* (1932), p. 301.

[22] *Ibid.*, p. 302.

[23] *Ibid.*, pp. 302–03. See also L. S. Brown, "Types, Occurrence, and Probable Origin of Texas Celestite," *Jour. Min. Soc. America*, Vol. 15 (1930), pp. 121–22. (Abstract.)

the overlying Walnut clay. As the theory requires, the evaporites should be found nearer the top in any cycle, the nearer the locality is to the shore line of reversal, in this case not far north.

2. *Origin of cap rock.*—Consideration of freshening influences in conjunction with regressive conditions into closed marine basins clearly demonstrates the origin of the upward sequence salt, calcium sulphate, calcium carbonate. This is the sequence observed in the cap rock of salt domes. The writer, in an earlier paper,[24] has recorded numerous other features of cap rock indicating its marine sedimentary origin, though at that time suitable processes whereby such a sequence could be developed were not understood.

3. *Indicator of age of salt.*—Deposits formed within a saturated solution of sodium chloride might be expected to be unfossiliferous. However, it has been shown that there exists a zone of progressively fresher water nearer the shore. It is reasonable to believe that some organic forms might be able to survive in this freshened zone, and it is to be remembered that within this zone calcium carbonate is precipitated. This more common phase of marine deposition above salt deposits has been found to contain fossil forms in several places, both within the Gulf Border and elsewhere. It can be stated, therefore, that the salt is of essentially the same age as that of the next overlying "normal" marine series, provided the original sequence is preserved. So far as the cycle itself is concerned it is of the same age, but the actual time of deposition within the cycle is slightly in advance of that of the anhydrite and retreatal limestone. Use of this principle will be made later.

4. *Initial dips.*—These considerations further indicate that precipitate formations, for example, limestones and anhydrite beds, are not necessarily deposited in a horizontal position, but may form with measurable initial dips. In other words, slight-to-moderate dips observed, at least regionally, in bedded rocks of precipitate origin are not necessarily conclusive proof of post-depositional tilting, as is illustrated later in connection with the Comanche formations flanking the Sabine arch. A recent paper of note along this line is that of Dake and Bridge.[25]

II. REGIONAL STRUCTURE OF GULF COASTAL PLAIN

Though from the standpoint of salt the Gulf Border province is broadly a geographic unit, there are within it five distinctly segre-

[24] Levi S. Brown, "Cap-Rock Petrography," *op. cit.*

[25] C. L. Dake and Josiah Bridge, "Buried and Resurrected Hills of Central Ozarks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 7 (July, 1932), pp. 629–52.

gated areas of known salt occurrence—the Coastal, the Texas interior, the Louisiana interior, the southwest Texas, and the Smackover areas—separated by extensive tracts in which salt, either as domes or otherwise, has not been found. The belt of coastal domes, containing a majority of those known, parallels the present coastline from Mississippi River to Mexico, extending 75 miles inland. Paralleling this, also 60–75 miles in width, is a "barren" belt, beyond which lie the Texas and Louisiana interior salt-dome areas. The Texas and Louisiana areas are separated by 100 miles or more of "barren," or salt-domeless, area under which occurs the Sabine arch, and a third "barren" tract lies between the Louisiana interior area and the Smackover area 75 miles northeast. For brevity these are referred to as the Coastal, Sabine, and Smackover barren belts.

Since the thin salt bed in southwest Texas has been completely penetrated and the age of the overlying and underlying formations determined, the age of the salt there is not open to question. The southwestern locality is separated from the other salt areas of the Gulf Border by very broad tracts wherein massive salt beds are unknown. Because of this wide separation, and because the age of the salt is evident, this salt area has no pre-eminent importance in this paper, and is not considered further.

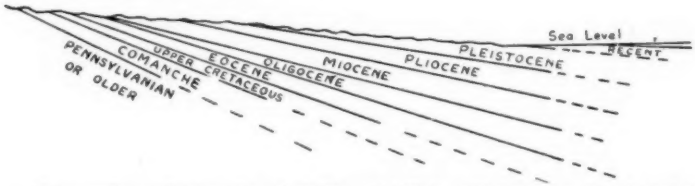


FIG. 5.—Generalized section of Gulf Coastal Plain, with known geology included within solid lines. Approximate scale: horizontal, 1 inch equals 100 miles; vertical, 1 inch equals 10,000 feet.

In Figure 5 is presented a generalized section of the Gulf Coastal Plain, which is made up of sedimentary formations with dips generally south or southeast that gradually decrease from the Comanche to the present. The dip of the Beaumont clay is 1 or 2 feet per mile, and the dip of the Comanche, or the Upper Cretaceous where the Comanche is absent, is uniformly 45–55 feet per mile from Maryland to Texas, with the exception that in southern Arkansas, on the southern flanks of the Ouachita nappes, it increases to 125 feet per mile.

Intercalated at various horizons are beds of lignite, in nearly discontinuous forms. These are more prominent in the Tertiary sedi-

ments, and are developed especially well in the Lower Eocene. Though their extent and thicknesses are well known far back from the gulf, they are believed to extend down the dip of their respective formations, as they have been encountered at various depths in many wells, one at Galveston reporting lignite at about 2,000 feet, of course at a much younger horizon.

The progressive decrease in dip has been explained as due to progressive tilting of the sea floor during sedimentation. Though localized crustal movement in that area is possible and undoubtedly has occurred, it must be remembered that a decrease in dip is the natural result of cyclical sedimentational processes. As was shown in Part I, the sediments deposited during any transgressive-regressive cycle are wedge-shaped in section. Though a single wedge may not represent an important divergence in outline, a series of such wedges, similarly superposed, introduces prominent changes in attitude. With the dozen or more transgressions of the sea, from the Comanche to the present, evidenced by the existing strata and unconformities of the Gulf Coastal Plain, the sea passed widely back and forth over the land, from and to the same source. Thus the sediments represent a series of wedges, similarly superposed, and the dips gradually decrease accordingly.

Other evidence supports this explanation. For example, if it be assumed that the strata were deposited horizontally upon the sea floor, there results a lack of explanation as to how clastic sediments can be distributed uniformly over wide areas, why the formations increase gradually in thickness to the south, which was away from land, and how the known unconformities were introduced, all of these questions being answered by recognized depositional and erosional mechanics of contemporaneous sedimentation and shore migration over an initially dipping floor. Moreover, the uniformity of dip of the pre-Cretaceous floor, 45–55 feet per mile from Texas to Maryland, is hardly fortuitous. More likely this represents the average slope of marine erosion as the initial sea slowly advanced over the land.

Another observation on the sediments of the Gulf Coastal Plain is that there exists a progressive change from strictly marine to deltaic deposition from the Cretaceous to the present, and the Tertiary sediments are almost wholly of deltaic accumulation. This means more than the simple building of deltas at a static water level. No seashore is free from river drainage, and no river enters the sea without contributing some load of sediment. The latter is attacked promptly by waves and littoral currents, and thus distributed along the shore, with the mode of deposition at any point more clearly marine the

farther the material gets from the mouth of the river. The degree to which the delta will be dissembled depends upon the distance between rivers, the rate and amount of their load contribution, and the configuration of the coast, that is, the strength of the waves and currents. With rivers closely spaced, a heavy discharge of sediment, and a protected coast, there are found optimum conditions for the formation and preservation of deltaic structures, and with the shore migration these structures may be spread almost uniformly over wide areas.

Such indeed are the conditions that prevailed through the Tertiary along the Gulf Border. Abundant lignites testify to an exceptionally moist climate, thus to heavy precipitation and land drainage. The Tertiary is regarded as having been more moist than to-day, and to-day the Gulf Coastal Plain is traversed by numerous important rivers, closely spaced. Not far in the rear were the rising or newly uplifted Rocky Mountains, providing an abundance of erosional debris, together with great quantities of unconsolidated Cretaceous sediments just exposed through which the rivers made their new courses. The Gulf Coast shore line always has been shielded from the more violent attacks of the sea common to the eastern Atlantic seaboard.

These considerations are in further support of the conclusion of deltaic origin found in the sediments themselves, wherein occur crossbedding, discontinuity, and lenticularity, in vast accumulations of terrigenous material. Pronounced individual deltas have been described,[26] most notably that of the Brazos-Trinity Pleistocene delta mapped in such clear detail by Barton, though this represents but a comparatively thin Pleistocene cover over great quantities of deltaic sediments of earlier accumulation. The general absence of limestones in these sediments is explained by the temperate Tertiary climate and the exceptional freshening of the sea borders through copious precipitation and land drainage.

The thick deltaic accumulations are of great importance in their genetic relation to doming effects in the underlying salt. About fifty per cent of the known Gulf Coastal domes lie within the boundaries of the Brazos-Trinity delta mapped by Barton, and most of the remainder occur beneath the delta of the Mississippi. The rest are scat-

[26] D. C. Barton, "Surface Geology of Coastal Southeast Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 10 (October, 1930), pp. 1301–20.
"Deltaic Coastal Plain of Southeastern Texas," *Bull. Geol. Soc. America*, Vol. 41 (1930), pp. 359–82.
L. C. Reed and O. M. Longnecker, "A Yegua Eocene Delta in Brazos County, Texas," *Univ. Texas Bull. 2901* (1929).

tered beneath the deltas of the Nueces and Guadalupe rivers, and the Rio Grande.

The Texas and Louisiana interior domes are found within the earlier deltaic accumulations of the Trinity and Red rivers. Red River was described by Powers[27] as "probably a very old drainage system which made its way across the Gulf Coastal Plain as new formations were successively elevated."

In the Gulf Border province it is the excessive weight of this rather quickly accumulating deltaic load that supplies the pressure largely responsible for flowage of the underlying salt, a factor that is considered more in detail later, in Part III. The saturation of this material with occluded water and its unconsolidated character facilitate its penetration by the salt pillars.

The character of the pre-Comanche or pre-Cretaceous floor (Fig. 5) on which the sediments accumulated may be described by reference to several recent papers. Stephenson[28] writes:

> The region which we now call the Gulf Coastal Plain was, in early Cretaceous time, a land area characterized by low rolling topography, probably fitting quite well our commonly accepted concept of a peneplaned surface. The area was not, however, a coastal plain, but a continental tract underlain by more or less folded Paleozoic rocks, which, during Triassic, Jurassic, and early Cretaceous time, had been beveled by erosion to an approximate base level. Just how far this land extended toward the south we do not know, but the assumption seems justified that it included all of the area that now lies above the level of the Gulf of Mexico and probably extended at least to the submerged edge of the continental shelf.

Sellards[29] reports that out of 35 wells passing through the Cretaceous in the Balcones fault zone 3 encountered schist, supposedly pre-Cambrian, in the Luling field, and all of the others entered hard and altered Paleozoic rocks of Ouachita facies, at depths ranging from 266 to 3,535 feet. Miser and Sellards[30] discuss 19 wells in the vicinity of the Texas-Oklahoma-Arkansas junction, all of which passed from the Cretaceous into rocks of Ouachita facies. Veatch[31] speaks of the "old

[27] Sidney Powers, "The Sabine Uplift, Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4, No. 2 (1920), pp. 117–36.

[28] L. W. Stephenson, "Major Marine Transgressions and Regressions and Structural Features of the Gulf Coastal Plain," *Amer. Jour. Sci.*, 5th ser., Vol. 16 (1928), p. 279.

[29] E. H. Sellards, "Rocks Underlying Cretaceous in Balcones Fault Zone of Central Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 7 (July, 1931), pp. 819–28.

[30] H. D. Miser and E. H. Sellards, "Pre-Cretaceous Rocks Found in Wells in Gulf Coastal Plain South of Ouachita Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 7 (July, 1931), pp. 801–18.

[31] A. C. Veatch, "Geology and Underground Water of Louisiana and Arkansas," *U.S. Geol. Survey Prof. Paper 46* (1906), p. 69.

Triassic land surface, or 'bed rock'," and Monroe[32] reports hard Carboniferous rocks immediately underlying the Tuscaloosa in several deep wells (3,200–3,900 feet) in the Jackson gas field, at Jackson, Mississippi. Van der Gracht[33] writes:

> A very long time intervened between the late Carboniferous and the deposition of the Lower Cretaceous. Of what happened in this time interval on the Gulf Coast, extremely little, if anything, is known.

Thus the floor, wherever known, either in bordering outcrops or in wells appreciably within the Cretaceous boundary, is composed of Paleozoic rocks, Pennsylvanian or older, which extend southward or southeastward an unknown distance down the dip. The relatively smooth and peneplaned character of this floor probably is due to shore erosion by the advancing sea, as previously stated.

No marine Permian, Triassic, or Jurassic sediments between the Cretaceous (or the Comanche) and this Paleozoic floor are known in the Gulf Border area. Whether they exist, intercalated in this position farther down the dip than yet observed, also is unknown. Probably they do, for marine Jurassic formations are known in southern Mexico and Cuba, and salt described as Permian in age has been reported also from southern Mexico. If so, they must occur much too far down the dip to be associated with the Gulf Border salt deposits, as shown in Part III. Probably marine formations of these ages never were deposited between the Cretaceous and Paleozoic where that contact now can be observed, for if they had been deposited it is very unlikely that every trace should have been removed by erosion from the broad areas of the Gulf Border.

But somewhere within the sediments, whether Permian or younger, above this Paleozoic floor lie great masses of bedded salt, it being understood to be generally conceded that the salt is of marine origin and that it is younger than the Pennsylvanian. Its precise horizon has remained obscure, due to the fact that the salt is known almost solely at the tops of domal uplifts, and few observations of wells completely penetrating the salt are on record as such. Whatever its horizon, if this is a continuous bed of salt underlying the whole of the Gulf Border province, if the deltaic load is similar in all parts of the Gulf Border province, as it appears on the surface to be, and if the deltaic load is largely responsible for the doming effects, then why are there such broad and well defined areas where salt, either as domes or

[32] Watson H. Monroe, "Pre-Tertiary Rocks from Deep Wells at Jackson, Mississippi," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 1 (January, 1933), pp. 38–51.

[33] W. A. J. M. van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *ibid.*, Vol. 15, No. 9 (September, 1931), pp. 991–1057.

otherwise, is unknown? The answer is either that the salt is not a continuous bed or that the subsurface geology of the barren belts differs in some way from that in the domal areas, or both factors combined.

Through several years of close study, the writer has noted many features of the salt domes, in their form, structure, relation to enclosing beds, character of cap rock, et cetera, which clearly indicate the salt in the several areas to be of different ages. These features are presented in Part III in connection with the age of the salt, but are immaterial to the present discussion. The important point here is that, if the several areas represent different ages in the salt, they also must represent different basins of precipitation, so that they may be designated as the Smackover, Texas interior, Louisiana interior, and Coastal salt basins. Furthermore, if they are structurally separate salt basins then the separating structures must be of pre-salt age. Surficially the salt basins are separated by the barren belts, and beneath these there must occur, deeply buried, the higher lands enclosing and bordering the salt basins. From these considerations there is evidence both that the salt is a discontinuous stratum and that the geology underlying the barren belts differs from that underlying the domal areas. It is the purpose of this paper to seek evidence other than the salt itself for the existence and age of these inter-salt structures.

On an erosional plain, the truncated edges of inclined strata appear as parallel bands, provided the individual thicknesses and the shape of the floor of deposition remain uniform. Accordingly, around the southern and southeastern flank of the Llano monadnock bend the parallel outcrops of the beveled Coastal Plain formations, but very shortly on the northeast the bands separate into two groups, the Cretaceous and Lower Eocene flaring widely toward the north as far as southern Illinois, and the post-Eocene continues east-northeast directly across the Mississippi embayment at least as far as central Mississippi, passing immediately south of the Texas and Louisiana interior salt areas. The wide intervening territory is represented principally by the Lower Eocene. In this divergence of outcrops there is reflected some pronounced change in the shape of the depositional floor; it can not be due to thickening of the Lower Eocene formations, for they are here much thinner then they are down the dip toward the south. Also, the dips in this wide territory are so low that Dumble[34] wrote that it was very difficult to trace the members of the different Lower Eocene formations.

[34] E. T. Dumble, "Report on the Brown Coal and Lignite of Texas," *Geol. Survey of Texas* (Austin, 1892).

The terrace form of this flat Eocene land in the Mississippi embayment is indicated by its termination along the southern border with the Angelina-Caldwell flexure, and it is of more than passing importance that its southern boundary also marks the northern boundary of the Coastal barren belt. The great length of the Angelina-Caldwell flexure along the strike, and its form, were described by Dumble,[35] who wrote that

> Towards their southern side the beds belonging to this division [the Lignitic beds of the Timberbelt division—L.S.B.] present the initial flexing so largely developed throughout the immediately overlying marine or glauconitic beds. These undulations occur at many places south of the Sabine River, in Smith County, beginning a few miles south of Lindale, and extending as far south as Bullard, where the beds pass under the glauconitic sands of the Mount Selman series. From whatever cause this flexing may have arisen, it is evident that the same action involved the structure of these as well as the succeeding beds, although they are widely separated in composition and the conditions under which they were deposited. A striking resemblance between the flexures of the two sets of beds, leading to the conclusion that this bending took place after the upper deposits had been laid down, is their general coincidence with each other and their uniform tendency to a northeast and southwest course, or a course approximately parallel to the old Cretaceous shore line. . . . Toward the southern border these deposits [the Cook's Mountain—L.S.B.] assume a general uniform southeast dip of nearly sixteen feet to the mile. The southern border, so far as has been traced, breaks off somewhat abruptly, and is strongly indented by several great bay-like openings, and probably more than one long, narrow, river-like channel, through and among which the succeeding deposits have been formed in an unconformable manner.
>
> The southern boundary can be easily traced from its entrance into the State in Sabine County, through San Augustine, Nacogdoches, Cherokee, and Houston, as far west as the Trinity River, and probably much further. . . .

The present definition of the Angelina-Caldwell flexure as marking the beginning of the great southward thickening and increase in dip of the Wilcox formation is true but insufficient at least in that it neglects a most important aspect, the cause. The flexure clearly is a depositional feature. It can not be explained as a post-depositional fold in the Wilcox, for this fails to explain the great southward thickening not only of the Wilcox but of all subsequent formations. On the other hand, with a pre-Wilcox terrace an abrupt thickening in all formations beyond its scarp is the natural result of repeated washing of abundant sediments slowly back and forth over the terrace with the progress of the repeated marine cycles of the Tertiary. It also is true that as the sediments are built up thicker and thicker above the terrace a gradual decrease in the steepness of the scarp

[35] E. T. Dumble, *op. cit.*, pp. 132, 142–43.

occurs, and yet more notable is the gradual removal of the upper edge of the scarp back into the terrace itself.

Eastward from central Texas the terrace includes under its southern portions the Texas interior salt area, the Sabine arch, the Louisiana interior salt area, the Monroe uplift, and the southern portion of the Arkansas basin. A general west-east section, drawn across the northern part of the Sabine arch, has been published by Lahee,[36] in which the relations of these different features are shown. Extending down within the terrace is the Sabine "peninsula," with Comanche and later sediments dipping from it toward the west and toward the east into the Texas and the Louisiana "synclines" respectively. If these are true synclines, pitching toward and opening on the south, the outcropping bands of Miocene and later sediments should follow in and around the borders, outlining the Sabine peninsula. They do not do so, but strike directly across both of the synclines.

The Sabine peninsula on the south is terminated by the Angelina-Caldwell flexure. Regarding the peninsula as a structural terrace and the flexure a depositional feature, as already described, this is the situation to be expected. But in the same light it is to be expected that the flexure should bend around and outline the flanks of the peninsula as it does on the south. It does not do so, but continues its strike east and west from the terminus of the peninsula across the two synclines.

From these considerations it is evident that the synclines can not be true synclines, but must be separate basins closed by some structure on the south. The Eocene depositional terrace exists above these two basins, a condition that could not be possible if there were not some structure on the south to withhold the entering sediments and build up the terrace. Once the basins were filled, continued sedimentation built the terrace higher, and thus extended the Angelina-Caldwell flexure much farther east and west than the boundaries of the Sabine arch.

Structural contour maps of the two basins, drawn on the Woodbine or the Nacatoch sands, show the basins as shallow synclines on either side of the Sabine peninsula. At these horizons the basins do have the form of synclines, but this simply means that the basins and the Sabine peninsula are older than the Woodbine, and that the basins were filled prior to Woodbine time. Since sedimentation was going on above the Sabine structural terrace at the same time the basins were being filled, it is evident that successive horizons should

[36] F. H. Lahee, "Contributions of Petroleum Geology to Pure Geology in the Southern Mid-Continent Area," *Bull. Geol. Soc. America*, Vol. 43, map, Fig. 3 (1932).

be found higher there than on either side, so that younger horizons should give synclinal rather than basin-like contours.

With reference to older horizons, another feature indicating complete enclosure of these two basins on the south is observed in the thick red beds of Glen Rose and Lower Trinity age found in the Louisiana basin. This basin is not very far south of the northernmost shore line of the Comanche sea. Red beds, representing the final clastic sediments of recessional seas, are the first deposits of any marine cycle to be attacked by sub-aerial erosion. Yet here there are very thick accumulations, a condition that could not exist were it not that they were caught in a basin from which they could not be carried away.

Another feature emphasizing restriction if not closure on the south of the Tyler and northwestern Louisiana basins is found in the artesian waters of those areas. Saline springs and ponds, in many places the sources of outflowing streams, exist above the interior domes, and in the southern portions of the basins wells have encountered copious artesian flows of heavily saline water. Similar phenomena are unknown within the barren belt on the south. It seems evident that the northern boundary of the barren belt marks some underlying constriction of the aquifers.

The wide Eocene terrace, marked on the south by the Angelina-Caldwell flexure, has an important bearing on the localization of the lignite and limonite deposits in Texas. Abundant lignites generally are held to indicate areas of greater subsidence and sedimentation. Though this in a limited sense is true, it is vague and insufficient in its connotation. It fails to give a clear picture of the physiographic conditions and boundaries prevailing at the time of the lignite formation in Texas, and it encounters serious difficulties in explaining why the most profuse development of the Wilcox lignites is found high up on the western flank of the Sabine arch, which has been regarded as a persistently positive area.

If, on the other hand, the genesis of lignites is examined with regard to initial dips and from a physico-chemical standpoint, a clearer conception is obtained. For example, wood and other carbonaceous materials can not be preserved unless promptly buried in a non-oxidizing environment. It follows from this that heavy lignites can occur only in the basal formations laid by transgressive seas. The several marine transgressions of the Gulf Coast Tertiary can be determined easily by this criterion, which is demonstrated especially plainly in the Eocene of Alabama. Some lignites may be preserved in rapidly accumulating continental sediments, as found for instance in

the Tuscaloosa of Alabama, but these are inconsequential as compared with the widely distributed deposits of marine burial.

It follows further that, if lignites indicate advancing seas, it is unnecessary to postulate widespread swamp topography, for as the shores advance up the wooded slopes the carbonaceous material is worked over, gathered, and enclosed in growing deltaic marshes and lagoons where it is discovered eventually as lignite. The lenticularity, variability, attitude, and largely coniferous composition of the Eocene Gulf Coast lignites are entirely in harmony with this view.

Another deduction refers to climates. Abundant lignites indicate a very humid or moist climate, for such a climate produces both a luxuriant vegetation and an excessive run-off bringing an abundance of sediment promoting quick deltaic burial. Arid climates support but sparse and stunted vegetation; rivers tributary to the sea are small and widely spaced. Thus the basal deposits of a sea advancing under an arid climate have been formed under conditions distinctly unfavorable to deltaic development, and little carbonaceous material at best has been available for burial. Thus the degree of deltaic and lignitic development in the basal series of a marine cycle is an accurate indicator of the climate then prevailing.

With regard to the Eocene terrace, the waters in the gulf repeatedly rose slowly up the outer southern wooded slopes, burying the carbonaceous material that is now found as lignite down the dip of the several formations. Eventually the waters reached the top of the terrace; here the flat lands were more favorable to a luxuriant vegetation and the development of swamp topography, if such is necessary, and it is highly significant that here the heaviest deposits of lignite today are found. Further, the genesis of limonite ores is ascribed to swamp accumulation, and it is also significant that the limonite deposits of East Texas are well developed in the wide temporary Claiborne swamp up on the terrace.

This digression into the climatic significance of lignites is referred to in Part III. The purpose of the foregoing discussion of lignite origins is to present confirmatory evidence of a pre-Wilcox terrace over the Texas and Louisiana interior salt basins, which is evident in the localization and attitude of the Tertiary lignites and limonites found above the basin in East Texas. This terrace could not exist over the basins on either side of the Sabine arch unless there were some structure on the south to withhold the sediments and thus build up the terrace.

Thus the form and structure of the Coastal Plain sediments clearly reflect a buried ridge, trending east-northeast across the

Mississippi embayment south of the Texas and Louisiana interior basins, and underlying the Coastal barren belt. The existence of this ridge is strikingly supported by regional gravity observations, for it is the locus of a distinct gravity "high," and gravity "lows" occur over the Texas interior salt basin north of the ridge and over the Gulf Coast geosyncline on the south.[37]

Concerning the age and nature of the ridge crossing the Mississippi embayment, and the ridge as the cause of the terrace as it exists over the interior basins, some evidence is available. That it is older than the Glen Rose is shown by the retention of thick Glen Rose sediments behind it, as previously described; also it may be observed that it must be older than the interior salt, which itself must be at least as old as middle Glen Rose.[38] The gas field at Jackson, Mississippi, lies on its strike toward the east, and here deep wells have passed from the Cretaceous into Pennsylvanian or older sediments, hard and partially metamorphosed, that were steeply inclined.[39]

Its trend eastward beyond the Jackson field is uncertain. It may bend southward, as evidenced by the Miocene outcrop, in which case its arcuate form and parallelism to the Ouachitas suggest it to be one of the buried southerly Ouachita nappes as mentioned by van der Gracht.[40] Or it may continue eastward, and represent a continuation of the folds of the southern Appalachians, which pitch out of sight beneath the Cretaceous in central Alabama. In either case it is pre-Comanche. Again, Spooner[41] remarks, concerning the earliest Upper Cretaceous rocks laid down in the Louisiana interior basin:

> The lateral variation in the character and thickness of the basal beds (Bingen group) suggests that the sea advanced from the south and west, and that the sediments were derived from the Appalachian rather than from the Ozark mountain system.

Passing to Smackover, the existence of a separate basin is indicated on closely analogous evidence. For convenient reference, one of

[37] D. C. Barton, C. H. Ritz, and M. Hickey, "The Gulf Coast Geosyncline," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 12 (December, 1933), Fig. 2, p. 1451.

[38] H. J. McLellan, E. A. Wendlandt, and E. A. Murchison, "Boggy Creek Salt Dome, Anderson and Cherokee Counties, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 584–600.

[39] Watson H. Monroe, "Pre-Tertiary Rocks from Deep Wells at Jackson, Mississippi," *ibid.*, Vol. 17, No. 1 (January, 1933), pp. 38–51.

[40] W. A. J. M. van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 9 (September, 1931), pp. 991–1057.

[41] W. C. Spooner, "Interior Salt Domes of Louisiana," *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926), p. 280.

Spooner's[42] sections, west-east across the Smackover field, is reproduced as Figure 6.

With reference first to the Glen Rose series, there is observed a record of a marine cycle, complete except for the closing red beds, shown by lower Glen Rose transgression from the west, upper Glen Rose retreat toward the west, with the anhydrite making up the

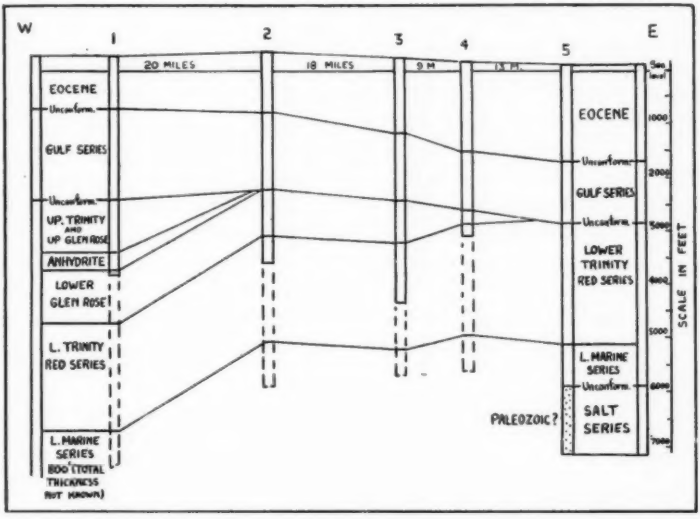


FIG. 6.—West-east section across Smackover basin. (After W. C. Spooner.)
1. Lenz *et al.*, Johnson No. 1, Sec. 24, T. 15 S., R. 26 W.
2. Humble O. & R. Co., Bodcaw No. 4, Sec. 9, T. 15 S., R. 22 W.
3. Louisiana O. & R. Co., Manley No. 1, Sec. 15, T. 15 S., R. 19 W.
4. Artex Oil Co., Smith No. 1, Sec. 31, T. 15 S., R. 17 W.
5. Lion O. & R. Co., Hayes A-9, Sec. 4, T. 16 S., R. 15 W.

middle of the series as is normally the case for evaporites. Smackover is very near to the northeastern boundary of the Glen Rose maximum inundation. This, together with the fact that red beds are the first sediments of any cycle to be removed by erosion, accounts for their absence from this section, and substantiates the unconformity indicated at the top of the Glen Rose series. Farther west (or southwest) the upper Glen Rose red beds should be found, since retreat was in that direction, and red beds do appear above the marine series of the

[42] W. C. Spooner, "Salt in Smackover Field, Union County, Arkansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 601–08.

Glen Rose in northwestern Louisiana. The section also shows the later Gulf invasion and Tertiary strata, following above the Glen Rose as usual, in this area, overlying a marked erosion surface.

Beneath the Glen Rose series, however, may be seen the latter half of a still earlier marine cycle, represented by nearly 2,500 feet of recessional red beds, as observed in the salt-discovery well. This brings up a question as to why this great thickness of Lower Trinity red beds should be preserved essentially in the same geographical situation from which the later Glen Rose red series was completely removed. The answer is that the Lower Trinity red series was deposited within an enclosed basin, and thus protected from fluviatile removal. In further support of this conclusion, note that for 40 miles or more westward the Lower Trinity red series was reached at about the same horizon and depth, but farther westward there is an abrupt increase in dip. Clearly the form of the Lower Trinity red series in this diagram reflects the complete filling of an enclosed basin, with further deposition of the red beds overflowing the basin and following the retreating Lower Trinity sea southwest.

Another feature evidencing the separate character of the Smackover basin is seen in the great thickness of the salt. At the time of salt discovery,

> opinion was general that a comparatively thin stratum would be penetrated which would be interpreted as the northern edge of the assumed mother salt bed from which the salt of the interior domes was derived. But the great thickness actually penetrated with the total thickness undetermined cast considerable doubt on this hypothesis and encourages the view that the Smackover salt may be intrusive in origin.[43]

The possibility that it may represent the central part of a separate deep basin seems to have been overlooked.

The great thickness was interpreted in Spooner's original description as due to doming, but it was stated that the doming must have been pre-Comanche, for the Comanche sediments show no evidence of differential uplift. It was thought that the top of the salt represented a post-doming erosion surface, with the age of the salt probably Permian.

These conclusions may be examined briefly. Salt flowage occurs in response to differential static or dynamic stresses, or both. The accumulation of a thick deltaic load has played an important part in effecting salt-dome intrusions throughout the Gulf Border province. Dynamic (faulting, folding, or overthrusting) movements have been

[43] H. W. Bell, "Discovery of Rock Salt Deposit in Deep Well in Union County, Arkansas," review by C. L. Moody in *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 10 (October, 1933), p. 1282.

important accessories in some, though these stresses are far more in evidence in the German and Roumanian domes. If the salt at Smackover is domed, it must be so through the influence of one or another of these two types of stress. 1. If the doming is due to static deltaic load, and is pre-Comanche as postulated, the conclusion follows that the Permian salt was buried to several thousand feet beneath unconsolidated incompetent material of post-Permian pre-Comanche accumulation. Further, this great accumulation was completely removed by erosion prior to Comanche time, for no physical trace of it is found in the Smackover section or anywhere else in the Gulf Border province. It seems quite unlikely that the salt could have been domed from this cause. 2. With reference to dynamic movements, there seems to be no markedly important crustal disturbance of pre-Comanche age in the Smackover area that can be dated with certainty as later than the Ouachita overthrusts (late Pennsylvanian or early Permian) and these would be pre-Permian salt. From these considerations it appears very doubtful that the thickness of salt encountered at Smackover represents a doming effect, and the conclusion of a separate deep basin is correspondingly strengthened.

In the preceding discussion of Figure 6, it may be observed that the interpretation is based on initial dips, which are accepted as such in the figure. It does not preclude the co-influence of uplifts or warpings, but explanation of the structures observed does not require the assistance of such postulates. The maximum dip illustrated in the figure is about 50 feet per mile, as compared with a maximum possible initial dip in an average sand of approximately 550 feet per mile, which is the tangent of the "angle of rest" (about 6°) for sand deposited in water. The assumption of initial dips in this case seems wholly justified.

It may be observed further in the figure that a ridge, representing the western or southwestern boundary of the salt basin, rising to its maximum in the vicinity of the Bodcaw well No. 4, is compatible with the known well data illustrated. The stratigraphy indicated below the dotted projections of the wells is conjectural only.

Thus the sediments in the Smackover basin indicate some structure enclosing the basin on the west, which in age is pre-Comanche. As to its form, the existence of 1,300 feet or more of salt within 40 miles of the wall enclosing the basin indicates the ridge to have a very steep eastern or northeastern slope. This, with its pre-Comanche age, suggests it to be one of the southerly buried nappes of the overthrust Ouachitas described by van der Gracht,[44] a structure similar in

[44] W. A. J. M. van Waterschoot van der Gracht, *op. cit.*

age and form to that previously described in connection with the structure underlying the Coastal barren belt.

The third barren belt of importance is represented by the Sabine arch, between the Texas and Louisiana interior salt basins, which was suggested, by Powers, to be a buried hill,[45] though he inferred too that the chief uplift was post-Wilcox. C. L. Moody[46] writes that the Sabine uplift had its beginning at least as early as Cretaceous time. Writers earlier in the century, before the days when salt flowage was recognized to bring up fragments of deeply buried but superposed horizons, allied the Wilcox inlier with the observation of masses of Cretaceous limestone 3,000 feet above their proper horizon in the northwestern Louisiana salt area, with the subsequently deleterious inference of extensive late or post-Cretaceous structural deformation. Van der Gracht[47] mentions the possibility that the Sabine arch may be a buried hill belonging to the Wichita (early Pennsylvanian) folding.

A few paragraphs previously some evidence was presented showing the Sabine peninsula to be pre-Woodbine, and the depositional significance of the Angelina-Caldwell flexure shows the peninsula to have been a broad terrace antedating Wilcox. Further evidence, based on initial dips, of its pre-Woodbine age is observed in McFarland's[48] section (Fig. 7) across the East Texas oil field, reproduced herewith for convenient reference. The history outlined by this section is as follows. With the Sabine arch exposed as a land area in pre-Woodbine time, the seas gradually rose. The three depositional zones, sand, shale, and limestone, moved upward with the transgressing shore. As the water level reached the top of the broad upland the source of clastic sediments disappeared, and further deposition of sand or shale could not take place. Hence the Woodbine could not occur over the top of the arch, nor could the Eagle Ford be deposited shoreward above the Woodbine. In contrast, the early shallow waters completely submerging the arch were rapidly warmed and evaporated, thus continuing for a brief interval the precipitation of the Austin limestone, not only over the edges of the flanking Eagle Ford and Woodbine formations, but also thinly over the top of the arch. Thus was effected the seal that prevented further upward migration of the East Texas oil.

[45] Sidney Powers, "The Sabine Uplift, Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4, No. 2 (1920), pp. 117–36.

[46] C. L. Moody, "Tertiary History of Region of Sabine Uplift, Louisiana," *ibid.*, Vol. 15, No. 5 (May, 1931), pp. 531–52.

[47] W. A. J. M. van Waterschoot van der Gracht, *op. cit.*

[48] P W. McFarland, "East Texas Oil Field," *ibid.*, Vol. 15, No. 7 (July, 1931), pp. 843–48.

The maximum dip illustrated in the figure is that at the base of the Woodbine, approximately 55 feet per mile, certainly not an impossible initial dip. The contrary explanation of post-Eagle Ford, pre-Austin uplift, with tilting and beveling of the Woodbine and Eagle Ford prior to Austin deposition, seems to the author untenable, for it fails to explain the individual thickening of the former two formations off the arch, it discounts the validity of the usual depositional sequence, sand, shale, and limestone, and it ignores the mag-

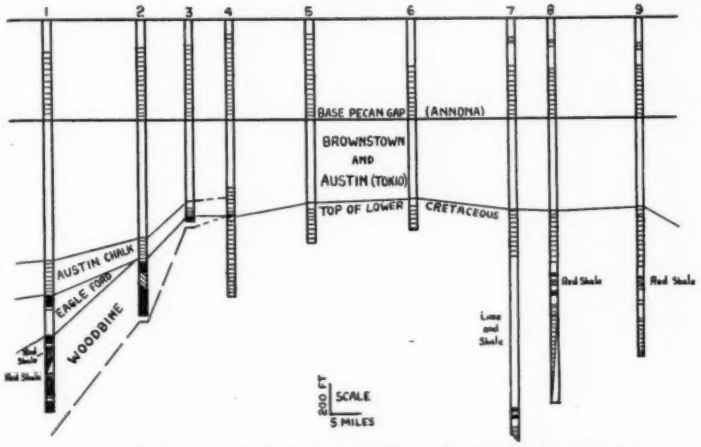


FIG. 7.—West-east section across East Texas oil field and Sabine arch. (After P. W. McFarland.)

nitude of marine sedimentational and erosional processes. It seems hardly possible that shore erosion of a sea retirement, succeeded by a period of sub-aerial erosion, could be followed by shore erosion of an advancing sea without the deposition of a basal sand-shale zone above the Eagle Ford and at the base of the Austin.

A yet earlier age for the Sabine arch is observed in many sections, for example, Pine Island and Monroe, generalized in Lahee's section[49] across the northern end of the Sabine peninsula. Here the Comanche sediments, including the Glen Rose anhydrite, are shown to increase in thickness down the dip toward the east and toward the west, a condition that can not be explained by post-depositional uplift and erosion, for the thickening occurs in each bed of the series. On the other hand, the wedge-shaped section is typical of cyclical sedimentation, with a gradual decrease in dip as deposition proceeds. Accord-

[49] F. H. Lahee, *op. cit.*, map.

ingly the Sabine buried hill is seen to be pre-Comanche, and the Monroe "uplift" is seen to be a similar structure.

This does not deny that post-depositional movements may have occurred in the south-central Arkansas, northwestern Louisiana, and northeast Texas area. It does mean, however, that the major sedimentational features of the area present questions that extensive post-depositional structural deformation can not explain, and which are made clear by a detailed analysis of marine sedimentational processes.

Thus the evidence shows the structures buried beneath the Coastal, Sabine, and Smackover barren tracts to be pre-Comanche, and some evidence has been presented showing an alliance between these structures and the Ouachita or Appalachian orogenies. Keith's[50] paper throws further light in support of this alliance, wherein is defined a "dome-basin" region which

> covers the interior of the United States west of the Appalachian Valley with its strong folds, and . . . reaches the Rocky Mountains in New Mexico and Texas. . . . The dome-basin region is crossed by two sets of major axes, one set trending northwest and the other trending northeast.

Again, van der Gracht's[51] discussion of the Permo-Pennsylvanian orogeny describes the two systems of folds, the Wichitas (early Pennsylvanian) trending west-northwest, and the Ouachitas (late Pennsylvanian or early Permian) trending east-northeast. These two intersecting systems of folds, whose pattern fits the geography of the interior salt areas, well may be the cause of the development of closed intermontane basins, and it seems reasonable to expect that basins developed between such strong folds should be deep as compared with their area.

Whatever the age of the salt, it can not be denied that the basins in which it accumulated were enclosed at the time that evaporation brought down the salt. Lest the attempt to link the age of these folds with the late Paleozoic orogenies be considered a vulnerable argument, let it be said that conclusive establishment of this age is immaterial. In the preceding analysis of the post-Pennsylvanian sedimentary structures, evidence has been presented showing that the inter-salt structures are pre-Comanche. This is sufficient if the age of the salt can be shown to be not older than Comanche. Evidence bearing on this point is presented in Part III on the age of the salt.

The method employed in the preceding discussion of the regional

[50] Arthur Keith, "Structural Symmetry of North America," *Bull. Geol. Soc. America*, Vol. 39 (1928), pp. 321–86.

[51] W. A. J. M. van Waterschoot van der Gracht, *op. cit.*

structure and history of the Gulf Coastal Plain reveals interesting points with regard to the physiographic development at various times, for example, the origin of the incised meanders of Colorado River northwest of Austin, the development of antecedent streams, and gulfward growth of the rivers. These problems, however, merit rather extended discussion, and seem irrelevant to the question of age and formation of the salt. For these reasons this phase of the Gulf Coast geology is not given further consideration in this paper.

III. AGE OF SALT

INTRODUCTORY

1. *Salt can not be older than Comanche.*—The experiments of Usiglio in the evaporation of sea water have shown that sodium chloride does not begin to crystallize until 0.9 of the water in the solution has been removed. This fact leads to an important deduction with regard to the evaporation of sea brines in natural marine basins, inasmuch as the level of the solution surface within the basin subsides to a marked degree. Natural marine basins generally have more or less gently sloping walls. Subsidence of solution level in a basin of such form is marked by a pronounced lateral retreat of the shores into the basin, so that, by the time sodium chloride saturation has been reached, precipitation of this salt is restricted to the relatively small and deeper central portions of the basin.

In other words, heavy marine salt deposits must be surrounded, initially at least, by very broad bordering areas of other deposits essentially of the same age as the salt. As shown in Part I these border deposits include, generally zonally distributed from the salt outward, calcium sulphate (often as anhydrite), limestone, and the clastic shoreward facies usually in the form of red beds. With inward retreat of the shores these border facies are brought down on top of the salt itself, so that they occur not only above the salt but widely overlap it as well. While such border deposits are early subjected to increasing erosional destruction with the progressive retirement of the sea in the usual marine cycle, they can not be removed from the enclosed salt basin by fluviatile erosion.

In general it is not difficult to determine the age of the bordering sediments, and through them to fix the age of the salt. For example, the salt deposits of Stassfurt and Sperenberg, in Germany, occupy only a small area as compared with that of the Zechstein sea basin within which they were concentrated. Far on either side of the salt the Permian strata can be identified and correlated with certainty.

The known Permian deposits of the western United States cover portions of several states, though the ultimate salts from this Permian sea occur only within the restricted boundaries of the Kansas and the Texas-New Mexico areas. There is no confusion as to the age of any of these salt deposits, for even if the lateral gradation of salt into the bordering Permian sediments were entirely concealed from observation the circumstantial evidence in the surrounding formations is convincing.

The salt deposit within the Gulf Coastal Plain is one of the largest, if not the largest, in the world. Surely there must have been associated with this salt very thick and far-flung sediments of a border facies. It is unthinkable that they should have been completely obliterated, nor can it be supposed that so great a sea could have existed long enough to form a salt deposit of such magnitude and yet leave no sedimentary record of its former existence other than the salt itself. Even if the border facies had been completely removed by erosion it is difficult to see how the salt itself could be preserved sufficiently from that erosion later to form domes 3,000–5,000 feet in height (interior domes).

Outward from the known salt areas of the Gulf Coastal Plain there are encountered successively Tertiary, Cretaceous (including Comanche where present), and Pennsylvanian or older rocks. The Tertiary rocks can not represent the associated border facies, for the Boggy Creek[82] section shows the salt (Texas interior salt) to be at least as old as the Glen Rose. The salt can not belong to the Pennsylvanian or older section, for, in its proximity to these outcrops, these rocks surely must reflect some associated saline facies. Not only are such facies absent, but the doming effects in the salt are quite unrelated to the profound Pennsylvanian and early Permian orogenic movements. Hence, the salt must be younger than the Pennsylvanian.

Intervening between Pennsylvanian time and Comanche time are the Permian, Triassic, and Jurassic periods. Evidence of high temperatures and aridity during the Triassic and Jurassic may be found in various parts of the world, and such evidence is especially prominent in connection with the Permian, but it is no argument to say that the Gulf Coastal salt must be of Permian age because the Permian was a time of world-wide aridity and salt formation. Heavy marine salt deposits require enclosed basins, wherein evaporation can effectively concentrate the salt; without such basins the factor of climate has no significance. To fix the age of the salt, the associated border sediments must be sought within these closed basins.

[82] H. J. McLellan, E. A. Wendlandt, and E. A. Murchison, "Boggy Creek Salt Dome, Anderson and Cherokee Counties, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 584–600.

The Pennsylvanian-Cretaceous (or Comanche) boundary closely approaches the areas of the Gulf Coastal salt deposit; at Smackover the distance is hardly 50 or 60 miles, whereas in size the salt deposit stretches southward, at intervals, beyond the present shores of the gulf. If the sea in which this salt was concentrated was of Permian, Triassic, or Jurassic age, it is difficult to believe that every physical trace of border sediments should be removed to so close a boundary, reaching from south-central Arkansas to central Texas and beyond. Erosion must have removed the sediments even more closely in, for deep wells considerably within the Cretaceous borders likewise have passed directly into Pennsylvanian or older rocks. No marine sediments of these ages are known within the Gulf Coastal Plain. Of yet greater importance is the fact that such erosive removal must have been completed prior to Comanche time; otherwise, the well records just mentioned must have revealed rocks of an age intervening between the Comanche and the Pennsylvanian, though they might have been removed from outcrops beyond. Because of this fact, in connection with the magnitude of the salt mass and the proximity of the known Pennsylvanian-Comanche contact, it may be concluded with high confidence that the Gulf Coastal salt can not be older than the Comanche.

The Comanche and Cretaceous sediments represent the first known marine deposits laid above the Pennsylvanian or older floor. They are the only deposits in the Gulf Border province whose present or former areal extent and thickness are at all commensurate with the magnitude of the salt deposit. They are potentially the only known border deposits to the Gulf basin, and it is within them that the age of the salt must be sought.

2. *Mesozoic sea transgressions.*—The great Mesozoic inundation arose in the Gulf of Mexico, spread widely over the interior of the North American continent, and subsided again into the gulf. This was not a single unhesitating advance and retreat, but was the sum of a number of minor transgressive and regressive cycles. In order to determine the precise ages of the salt formed within the deposits laid down by this inundation, it is necessary first to establish the times of Mesozoic sea recession, for it has been shown that a closed basin is essential to salt formation, and that a retreating sea, in turn, is essential to the isolation of any basin.

For this purpose the Mesozoic section given by Hill and Vaughan[53] is well suited. Its completeness and clarity are due to the fact that the section is located on the southeastern flank of the Llano monad-

[53] *U.S. Geol. Survey Geol. Atlas, Austin Folio 76* (1902).

nock, which, throughout Mesozoic and at least early Tertiary time, was very nearly the axis of the regional tilting that more severely interrupted the stratigraphic sequence on either side but affected that on the axis itself but slightly in comparison.

Following the movements of the sea by the lithologic changes exhibited within this section, in accordance with basic geologic principles, it is seen that four important regressions are indicated. These occurred, respectively, with the upper Glen Rose, the Georgetown, and the upper Washita (Buda), of which the first two are the more important, and lastly the great retreat closing the Mesozoic era, signified in this area by the thick regressive Taylor marl and Navarro clay. A principle developed in Part I is that the age of the salt formed with the retreat of any marine cycle is identified by the age of the border facies or of the immediately overlying regressional series of that cycle. Hence, according to this section, the salt may be found beneath upper Glen Rose, Georgetown, Buda, or Navarro formations, or their equivalents.

AGE OF SMACKOVER SALT

Proof that the salt can not be older than Comanche, and the fact that the Smackover salt is overlain by Lower Trinity sediments, seems to fix the age of the Smackover salt rather definitely. The question may be analyzed in more detail by reference again to Spooner's paper[51] and the section reproduced as Figure 6 in Part II. Beneath the Glen Rose cycle may be seen the latter half of a still earlier marine cycle. The salt, making up the middle series of the deposits of this cycle, is succeeded by the regressive marine facies, and this, in turn, by the final and usual red beds. The salt thus is of the age of this cycle, "beneath the oldest known Comanche strata" of the region, and hence of a retreat preceding the earliest shown on the Austin Folio section. According to this interpretation there is no unconformity above the salt, confirming the improbability of pre-Comanche doming and erosion as described in Part II.

The present interpretation, however, demands an unconformity between the Lower Trinity red beds and the overlying Glen Rose, for the red beds are deposits of receding seas, and the lower Glen Rose marks a re-advance of the sea. On this point it was stated that "the contact between the lower Glen Rose and the Lower Trinity red series . . . is irregular in the area of the Smackover field," and the relief is given as totalling 150 or 200 feet, a value that might be expected in a present day erosion surface in red beds.

[51] W. C. Spooner, "Salt in Smackover Field, Union County, Arkansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 601–08.

The local marine history thus begins with the inundation and filling of this border basin; with retreat of this earliest Comanche sea the basin was isolated, while the retreating shore laid over it an unfossiliferous marine series and red deltaic and continental sediments. The latter completely filled the basin and aggraded considerably beyond the southern rim in following the retreating sea. Then followed the Glen Rose cycle, and the Gulf and succeeding cycles, completing the history as shown for the Smackover area.

REGIONAL TILTING

During the progress of the Glen Rose cycle there took place a very broad but gentle regional tilting, downward on the southwest. This was the cause, at least in part, for the retreat of the Glen Rose sea from the northern Louisiana and Arkansas area, and perhaps for the isolation of the Texas and Louisiana interior basins. The tilting occasioned the development of the thick formations of the Fredericksburg and Washita stages in the Mexican and southwestern embayments, which thin toward the east and are represented in Louisiana and southern Arkansas only by poorly developed clastic border facies. The tilting was accompanied and followed by volcanic outbursts in northern Louisiana and southern Arkansas, as evidenced by the ash deposits above the Glen Rose rocks. The volcanism probably accentuated the local relief, but it can not be held responsible *in toto* for the folding in this area, which in Part II was shown to be pre-Comanche.

Toward the close of the Comanche there again occurred a regional tilting, in the reverse direction, so that the succeeding Upper Cretaceous invasion for the first time extended over and deeply submerged the southeastern area of the continent, but found its waters shallowing southwestward to nothing in southern Mexico, where the Senonian is wanting.

AGE OF TEXAS AND LOUISIANA INTERIOR SALT

These two basins are discussed together for the reason that several features point to the age of the salt as being the same in each basin. 1. The two basins line up parallel with the old Cretaceous shore line,[55] making it likely that they were isolated by the same sea retreat. 2. The two basins are enclosed on the south by an extension along the strike of the same buried structure, as shown in Part II, again making it likely that they were isolated by the same sea retreat. 3. Sections across the northern part of the Sabine peninsula show a bed of an-

[55] *Cf.* E. T. Dumble, "Report of the Brown Coal and Lignite of Texas," *Geol. Survey of Texas* (1892), pp. 132, 142–43.

hydrite underlying upper Glen Rose limestone, evidently anhydrite of one age, dipping down into each basin, and it is probable, for reasons to be shown, that the salt is associated with this bed of anhydrite. 4. Fragments of upper Comanche formations have been brought up by domal salt ascent in each basin.

In neither of these two basins, however, is there available a single section presenting the clear and complete detail of structure and history that is observed in the Smackover section just discussed. The evidence as to the age of the salt is hardly less conclusive, but it must be pieced together from several less complete sections.

The Boggy Creek[56] section in Texas, individually, perhaps, is the most instructive. Here the salt has been uplifted far less than it has in neighboring domes on the south, for example, Butler, Palestine, and Keechi. The elongate dome is associated with a pronounced linear fracture, through which the salt is just beginning to emerge, and the stratigraphic succession above the dome seems to be but little disturbed, as compared with other Texas interior domes.

Anhydrite, 10–140 feet thick, covers most of the Boggy Creek salt, and this is succeeded by Glen Rose limestone. Identification of the age of the limestone as Glen Rose seems secure, but whether it is upper or lower Glen Rose has not been stated. The fact, however, that the anhydrite underlies definitely identified Glen Rose makes it thoroughly reasonable to correlate this anhydrite with the bed underlying upper Glen Rose farther northeast in the basin on the flank of the Sabine arch. Since the slight uplift of the dome has not greatly disturbed the stratigraphic succession, it further is reasonable to conclude that the Boggy Creek section represents the normal saline sequence, according to which the salt should underlie the anhydrite, and be itself underlain by lower Glen Rose limestone. Whether the latter condition exists or not can not be shown at present, but if later work discloses the limestone above the anhydrite to be upper Glen Rose, and the lower Glen Rose to be absent above the dome, this point may be regarded as proved. With certainty, the Boggy Creek section shows the salt to be at least as old as middle Glen Rose, and available evidence is quite suggestive that it is not older.

From a physico-chemical standpoint, the thick middle Glen Rose anhydrite blanket known in northeast Texas, northwest Louisiana, and south-central Arkansas, in itself is proof that salt of the same age is associated with it in the same basins. As pointed out in Part I, the lowest temperature at which anhydrite, as opposed to gypsum, can form is 77°F., and precipitation as anhydrite at this temperature is

[56] H. J. McLellan, E. A. Wendlandt, and E. A. Murchison, *op. cit.*

possible only if the solution is saturated with sodium chloride. As the percentage saturation with sodium chloride decreases, the lowest temperature permitting crystallization of anhydrite rapidly rises; thus the postulate that 400 or 500 feet of anhydrite have been formed in this area without the solution reaching sodium chloride saturation demands climatic temperatures that become quite out of reason. It is because of this fact that the initial precipitate of calcium sulphate, preceding the salt in Usiglio's sequence, from an evaporating sea, is in the form of gypsum, with the final precipitate above the salt in the form of anhydrite, a succession noted by Ochsenius in the German deposits.[57] Also, gypsum was found beneath 1,160 feet of rock salt in the Savage Brothers' Test Well No. 1 on Drake's salt dome in Louisiana.[58] Again, it was pointed out in Part I (p. 1248) that the fauna of the Glen Rose limestone in the Homer field was a dwarfed facies.

Because the percentage saturations of calcium sulphate and sodium chloride differ widely in sea water (*cf.* Part I) the area of precipitation of calcium sulphate markedly overlaps that of sodium chloride. All of the wells in the Louisiana-Arkansas-Texas area that have completely penetrated the Glen Rose limestone-middle anhydrite section are located in this area of overlap. All are north of the known occurrence of salt domes. This fact again emphasizes the middle Glen Rose age of the salt. If the salt is earlier than the anhydrite, that is, not genetically related to the Glen Rose sea retreat, there seems to be no reason why domes of salt should not occur here as well.

The Winnfield dome lies in the far southern end of the Louisiana interior basin, and its cap rock is 1,000 feet thick. The age of the cap has not been determined, but it may be pointed out that nowhere in the Louisiana basin is any precipitate horizon of commensurate thickness known, other than the Glen Rose.

As a generalization, it may be repeated that the salt can not be older than Comanche, as previously shown. It can not be younger than middle Glen Rose, as shown at Boggy Creek. That there is no salt in the Texas-Louisiana interior basins of the same age as the Smackover salt (lowest Lower Trinity) has not been proved. Wells on the Sabine arch have reached but not penetrated the Lower Trinity marine series, below which the Smackover salt occurs. If there is salt at that horizon in Texas and Louisiana, it means that the Lower Trin-

[57] C. W. Cook, "The Brine and Salt Deposits of Michigan," *Michigan Geol. and Biol. Survey Pub. 15*, Geol. Ser. 12 (1914), p. 35.

[58] W. C. Spooner, "Interior Salt Domes of Louisiana," *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926).

ity sea retreat proceeded sufficiently far southward to isolate these two interior basins as well as the Smackover basin. The thickness of the Lower Trinity (Glen Rose) red series immediately south of the Smackover basin argues against but does not obviate this possibility. In any case, the sea retreat must first isolate the Smackover basin, for it is nearer to the shores at the maximum Lower Trinity inundation. While it may be granted that salt could be formed with the lowest Lower Trinity retreat, yet the evidence presented above shows that the salt as known in the Texas-Louisiana basins is closely associated with the Glen Rose retreat, and there is no evidence, either in the dome locations or in super-cap sediments, relating it to any other.

AGE OF GULF COASTAL SALT

The great Mesozoic inundation of North America arose in the Gulf of Mexico area. It transgressed toward the north, joining with the Arctic Ocean, and toward the east, rising over the Floridian plateau, to join with the waters of the Atlantic rising on the eastern side. Finally the waters slowly subsided, returning to the Gulf basin. Within this great marine cycle the small border basins were isolated by the lesser retreats of the minor included cycles, and salt deposits formed as just described in the three interior basins.

The Gulf Coastal basin, even though its outer boundaries may not be known, evidently is enormously larger than the three interior basins. Its southern boundary surely was far to the south of the present coast line, where the Cretaceous sediments are at least 10,000 feet below the surface. The deposits of the Mesozoic cycle show no retreats that brought the shore of the Cretaceous sea anywhere near enough south to isolate this basin, except the final great retreat of the Mesozoic. From the standpoint of isolation, without which no salt could have been formed, the age of the Gulf Coastal salt must be middle to late Upper Cretaceous. While this in itself is evidence of value as to the age of the salt, there are at least five more or less distinct lines of evidence, including paleontologic, stratigraphic, paleogeographic, sedimentational, domal mechanics, and climatic criteria, which offer confirmation to this conclusion. In the following brief review of these are found the reasons supporting the statement in Part II that the salt of the Gulf Border province could not be of the same age in all of the different areas of salt occurrence.

1. *Paleontologic.*—Knowing that high salt concentrations are inhospitable to aquatic organisms, it is evident that periods of desiccation will be reflected in the associated faunal development. Such portions of the faunal assemblage as are trapped in the isolated basin

eventually must pass to extinction. This is obvious if the basin dries up completely and remains thereafter as dry land. It is scarcely less true when, after a period of salt saturation and precipitation, the basin is flooded again with normal marine waters. The period of desiccation will be reflected in the variation between the faunas of the antecedent and the subsequent transgressions. The degree of the variation is a function of the desiccation interval, which is more or less directly related to the magnitude of the basin.

Fossil remains of the faunal assemblage should be found but sparingly within the area of the salt itself, but they are found far and wide within the sediments bordering the restricting saline sea. The border areas of the three interior basins previously discussed are contained within, but make up only a small part of, the extensive border area of the Gulf Mesozoic sea. In consequence, the concentration and precipitation of salt in these interior basins had but slight effect upon the faunal succession of the Mesozoic invasion as a whole. The lithologic and paleontologic succession indicates that the minor retreats did not leave the small border basins long, nor far behind. The integrity of the Gulf Cretaceous fauna could not have been seriously disturbed, for, as a general picture, it possesses a characteristic and unified aspect from the lowest Comanche to the highest Cretaceous formation.

But if the Gulf basin itself is isolated and evaporated to salt precipitation, the time involved in, and the effects produced by, its desiccation must become evident in profound faunal changes, for the Gulf basin is the fountain head of that Cretaceous faunal province. There is no faunal break within the Gulf Mesozoic strata that can be considered as at all a commensurate effect.

The final Upper Cretaceous retreat is the only one demonstrating faunal changes commensurate with the scale of the processes, time, and area involved. With this retreat the magnificent and varied fauna of the southwestern North American Mesozoic passed virtually to complete extinction, and, when the basin again became united with the open sea, the entering Eocene fauna presented a totally new aspect. Thus, from a paleontological viewpoint, the salt of the Gulf basin must be middle to late Upper Cretaceous.

While it may be argued that the Cretaceous-Eocene faunal break was a world-wide phenomenon, and that as such it may not be taken as evidence of aridity and salt formation within the Gulf basin, yet it must be noted that the floral break was small, thus indicating that some factor other than climatic change was responsible for the very marked faunal change in the Gulf basin. Moreover, the world-wide

faunal break indicates a world-wide withdrawal of the seas and a period of erosion around the borders of the continents. Certainly such a profound sea retreat should be expected to expose shallow marine barriers, and illustrates a likely time for the isolation of the Gulf basin. No such world-wide retreat is known elsewhere in the Cretaceous section.

2. *Stratigraphic.*—By employing the principles of saline stratigraphy developed in Part I, the same conclusion is reached. In the South Dayton dome, in Liberty County, Texas,[59] Navarro fossil forms were found in the upper part of the cap rock. The upward sequence, salt, anhydrite, calcium carbonate, has been shown in Part I to be the normal sequence developed in the deposits of a retreating, evaporating sea. This sequence has been observed above the salt in undomed sedimentary salt beds as shown elsewhere, and is the sequence developed in the cap rock above the Gulf Coastal domes. That this sequence should be very sparingly if at all fossiliferous is to be expected.

Many of the Gulf Coastal domes have brought up, included within fractures or other openings in the cap rock, fossiliferous fragments of intruded deeply buried Tertiary strata. If the Gulf Coastal salt lies at a horizon well below the Navarro, it is difficult to understand why but one of all the domes in that basin has retained a fragment of the Navarro as it penetrated the overlying strata, especially in view of the fact that the lower the horizon the earlier it is encountered in domal ascent, and probably more likely that it will be retained. On the other hand, if the salt is middle to late Upper Cretaceous, it is not remarkable that but one dome should possess a fossiliferous cap; rather it is remarkable that even one should.

In view of these observations, and the statement in the article referred to that the fossiliferous section is definitely a part of the cap rock, the conclusion again appears that the salt-cap-rock series is Navarro in age. As previously indicated, the apparently contemporaneous existence of a strong saline solution and organic forms does not militate necessarily against this conclusion. It must be remembered that the Navarro here is very much younger than the Navarro known in outcrops farther north, for the slow retreat was southward, so that the known fossiliferous Navarro outcrops considerably antedated the time of salt formation in the cycle. Also, the origin of the salt-cap-rock sequence has shown that a freshened zone exists near the shore, in which the existence of this relict fossil aggregation easily might be possible.

[59] T. E. Morrison, "First Authentic Cretaceous Formation Found on Gulf Coast Salt Domes of Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 8 (August, 1929), p. 1065.

3. *Paleogeographic.*—The outer boundaries of the Gulf salt basin are unknown. Whether the Floridian plateau, Cuba, Yucatan, and Mexico formed the eastern, southern, and western boundaries is not demonstrable. The size and depth of the present salt deposit, however, make this not improbable. There are three openings, excluding that to the Arctic, through which the Gulf sea has had communication with the external seas. These are the Straits of Florida, the Yucatan Channel, and the Tehuantepic Isthmus. The latter was open at various times during the Comanche, but is known to have been closed through late Upper Cretaceous and Lower Eocene time.

The geology in the vicinity of the other two openings is but imperfectly known. The literature contains an abundance of references on the subject,[60] but in the interest of brevity they can not be reviewed satisfactorily in this paper. Admittedly fragmentary, the evidence, such as it is, indicates the late Upper Cretaceous and early Eocene as a time when all of these openings were closed contemporaneously. Whatever its boundaries, it can not be denied that the salt basin was enclosed at the time of salt precipitation. It is significant that the evidence in the literature indicates the Gulf of Mexico to have been circumscribed by land connections at a time corresponding with that of salt formation deduced from other evidence.

4. *Lithologic.*—The lithologic character of the Midway (basal Eocene) succession is such as to indicate a rather rapid sea advance, very different from that occasioned by the more usual slow migrations

[60] 1. C. Wythe Cooke and Stuart Mossom, "Geology of Florida," *Florida Geol. Survey 20th Ann. Rept.* (1928).

2. C. H. Crickmay, "Jurassic History of North America," *Proc. Amer. Phil. Soc.*, Vol. 70 (1931).

3. L. W. Stephenson, "Correlation of the Upper Cretaceous of the Gulf Series of the Gulf Coastal Plain," *Amer. Jour. Sci.*, 5th Ser., Vol. 16 (1928).

4. Herman Gunter and Gerald M. Ponton, "Water Supply from Ocala Limestone," *Florida Geol. Survey 21st–22nd Ann. Rept.* (1929–1930).

5. Bailey Willis, "Index to the Stratigraphy of North America," *U.S. Geol. Survey Prof. Paper 71* (1912).

6. T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. America*, Vol. 29 (1918), pp. 615–30.

7. Carlos Sapper, "Geology of Chiapas, Tabasco, and the Peninsula of Yucatan," *Jour. Geol.*, Vol. 4 (1896), pp. 938–47.

8. Barnum Brown and Marjorie O'Connell, "Correlation of the Jurassic Formations of Western Cuba," *Bull. Geol. Soc. America*, Vol. 33 (1922), pp. 639–64.

9. Albert Wright, Jr., and P. W. K. Sweet, "The Jurassic as a Source of Oil in Western Cuba," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8, No. 4 (July–August, 1924), pp. 516–19.

10. Charles Schuchert, "Geological History of the Antillean Region," *Bull. Geol. Soc. America*, Vol. 40 (1929), pp. 337–60.

11. E. DeGolyer, "The Geology of the Cuban Petroleum Deposits," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 2 (1918).

12. J. Whitney Lewis, "Geology of Cuba," *ibid.*, Vol. 16, No. 6 (June, 1932), pp. 533–55.

of the shore. Differential levels prevailing at the time of the Midway incursion apparently were not greatly different from those at the time of the Upper Cretaceous inundation, or the Comanche.

By comparing the Upper Cretaceous and the Lower Eocene advances, it will be noted that the initial shore lines of the two were somewhat similarly located, though the retreat closing the Cretaceous probably carried the shore considerably farther south than that closing the Comanche. Both advances, the Upper Cretaceous and the Lower Eocene, reached northward over essentially the same territory, as far as the southern tip of the state of Illinois.

On the other hand, comparison of the deposits of the two advances reveals a marked dissimilarity. With the Upper Cretaceous advance the basal formations, Woodbine and Eagle Ford, were well developed, whereas the basal Eocene is characterized, in general, by thin and poorly developed limestones and sands.

These observations indicate the character of the Midway advance to have been considerably different from that of the Upper Cretaceous advance, a situation that may be explained by the flooding of a basin with a sub-sea level surface by the inbreaking of a rising external sea. As to the differential levels, the retreating Upper Cretaceous shore must have reached a position corresponding somewhat to the present shore, where the Upper Cretaceous is now at least 10,000 feet below sea-level, approximately a differential of that magnitude vertically to Cairo, Illinois. It may be argued that a differential of this magnitude did not exist at the beginning of the Eocene; yet, some differential did exist, for the Upper Cretaceous retreat was toward the south, and the Eocene advance arose in the south. It seems probable that the differential was of the order of two or three thousand feet at the minimum, at the time of the inbreaking of the Eocene waters.

In summary of these thoughts, the following facts hardly can be denied. 1. The Gulf salt basin was isolated from the open sea at the time of salt formation, whatever that time may have been. 2. Since that time, it has become reconnected with the open sea, for the sea exists above it to-day. 3. The level of the saturated salt solution must have been below that of the external inbreaking sea; otherwise, the sea could not have re-entered the basin and covered the salt-cap-rock strata with thick marine sediments. 4. Inundation under such conditions must have been far more rapid than inundation as accomplished by the more common marine floodings recorded in the geologic section. 5. There is no place in the sedimentary succession of the Gulf Border where such a change is as clearly marked as it is between the Upper Cretaceous and the Lower Eocene.

Cushman,[61] in studying the *Foraminifera* from a well at Marathon, Florida (Key Vaca), reports "an Eocene which is apparently typical of Panama and the West Indies, and unlike that of northern Florida," supporting two interesting conclusions. 1. This indicates close land connection between Florida and Cuba at least through the Lower Eocene. This is further paleogeographic evidence to that previously cited concerning the Gulf of Mexico at this time. 2. It seems probable that the Eocene sea refreshing the desiccated Upper Cretaceous basin entered through a southern avenue, as did its predecessor, the Jurassic sea, bearing a Lower Eocene fauna of West Indian and Panaman affinity. From the evidence of the differential levels already mentioned, and the prevalent major fault direction in the West Indies (east and west), it may be deduced that this great entering stream caused in some measure the canyon-like development of the Yucatan Channel. The strike of the channel and the position of the Campeche Bank add some weight to this view.

5. *Doming mechanics.*—The term "true cap" refers to origin rather than to exterior form. It is based on the texture, color, composition, and structure of the cap rock. In general, true cap is composed of massive coarse-grained anhydrite and/or brecciated light tan fine-grained limestone with calcite veins. The limestone shows its origin in part as an alteration of anhydrite, though there is some evidence that it is not entirely so.

Cap rock is absent above a few of the Gulf Border domes, but, where present, the cap rock in the foregoing sense, whether over interior or coastal domes, is true cap rock. If, however, exterior form is considered, the Gulf Border caps may be generalized definitely into two groups: (1) the very thin scanty accumulations as found at Palestine, Butler, Keechi, and other domes in Texas, and the Arcadia, Vacherie, and other domes in Louisiana; (2) the massive tablets observed at Hockley, Bryan Heights, Sulphur, and other domes in Texas and Louisiana. These two types appear to be distributed somewhat indiscriminately, but it must be remarked that caps of the second type are absent from the interior domes, with the possible exception of the Winnfield dome cap in Louisiana. For this general distinction there seem to be two relevant explanations, one being the poor development of the freshening sequence, and the other involving doming mechanics. With regard to the first, it will be remembered that 450–500 feet of anhydrite are known within the Glen Rose of northern Louisiana. This is in the off-lap area of the interior basin, and the wedge of salt, farther south, must lie somewhere within this wedge of anhydrite

[61] J. A. Cushman, *Florida Geol. Survey 13th Ann. Rept.* (1920), p. 33.

as shown in Figure 3, Part I. The anhydrite in the off-lap area has precipitated free from salt at the base according to Usiglio's sequence and at the top under the freshening influence. Several observations indicate the Glen Rose to have been a time of considerable aridity, according to which the freshening sequence here should be rather thin, and most of this anhydrite may represent Usiglio's basal precipitation. In other words, the wedge of salt thus may occur rather near to the top of the wedge of anhydrite, and the cap sequence thereby be thin. The probability of this interpretation, however, seems to be less, as an explanation for the thin caps, than that proposed in the following paragraphs.

With regard to doming mechanics, a few observations are presented here because of their apparent relation to the age of the salt. Massive marine salt beds in deep basins generally underlie considerable thicknesses of competent and incompetent strata. Of the competent strata the oldest is the cap sequence of anhydrite and limestone, though in the Texas-Louisiana interior basins and others there are several limestone horizons at intervals above the salt. If these covering materials, competent and otherwise, are of uniform distribution, character, and thickness, and are undisturbed, doming effects can not take place; for example, the thick salt beds of Michigan, New York, Kansas, or West Texas do not show domal accumulations.

Doming effects arise from stress differentials, of a static (load) or dynamic nature. In either case, flowage of the salt requires rupture of the competent beds. There is a fine distinction to be drawn as to whether the stress causing flowage of the salt is the same as that causing fracture of the competent beds, a distinction that seems not to have been discussed, and that to the author explains the prime differences between the European and the American salt domes. After fracture has occurred, from whatever cause, the static load, both of competent and incompetent material, always has its effect. In the European, especially the Roumanian, domes the flowage of the salt is distinctly related to the marked crustal deformation, evidently the cause of fracture in the competent beds as well, whereas in the American domes such crustal movement is far less evident and the form of the domes, rim synclines, et cetera, is much more clearly related to the operation of static differential stresses.

It is evident that very slight crustal movement can cause fracture of thick and numerous competent horizons, fractures that may be denominated as linear, longitudinal, or tangential, and that these generally will be on a regional scale. Such fractures present points of relief from static stress; the overlying load may cause flowage of the salt

through the openings thus produced, and it seems evident that the salt stock will be relatively free of a cap-rock burden, since the cap materials themselves constitute a bed of considerable competence. The cylindrical form of the stock is assumed because friction along the sides is least when the cross section is a circle. Also, the domes should occur at least occasionally in a linear arrangement, corresponding to the fracture below.

The interior domes of Texas and Louisiana seem to conform well with these conditions. The salt underlies numerous competent beds, beginning with the cap rock and Glen Rose limestone. The sections published by Powers[62] and Spooner[63] show the surface beds surrounding the domes almost without exception to be dislocated through tangential faulting, either normal or reverse. In the more deeply buried Boggy Creek dome the salt is just beginning to issue through an elongated fracture. Doming in the interior basins did not occur until after lithification of the Austin chalk, as witnessed by the hard massive blocks of limestone, Buda to Austin in age, on the edge of the Palestine stock. In the Palestine, Butler, Keechi, and other dome locations there is an evident linear arrangement. Finally, cap rock is practically absent from the interior domes, with the exception of that at Winnfield, Louisiana. On the other hand, the marked crustal folding, characteristic of the German and Roumanian domes, seems to be absent; the rim synclines and other features of the Mount Sylvan[64] and other domes testify to flowage of the salt chiefly under static load stress.

The question is relevant and valid, however, as to whether static differential stress alone is capable of effecting fracture of a competent bed as well as flowage of the salt. A prerequisite certainly is that the load must be very large in order to possess effective differentials, and the competent bed must be thin. It further seems evident that fracturing of the competent bed under such conditions preferably should take place in a circular form, for the shear affording relief for any area is least when that area is a circle.

These are the conditions which, in our present knowledge, seem to be present in the Coastal salt basin. No competent bed, other than the cap sequence, ever has been recognized above the salt; no frag-

[62] Sidney Powers, "Interior Salt Domes of Texas," *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926), pp. 209–68.

[63] W. C. Spooner, "Interior Salt Domes of Louisiana," *ibid.*, pp. 269–344.

[64] E. A. Wendlandt and G. Moses Knebel, "Lower Claiborne of East Texas, with Special Reference to Mount Sylvan Dome and Salt Movements," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), pp. 1347–75.

ment of any other competent bed, with the exception of the questionable fossiliferous section of the South Dayton dome as previously discussed, ever has been brought up by any dome. The salt and its cap sequence are overlain by 10,000, perhaps 15,000 or more, feet of unconsolidated incompetent sands and shales, of deltaic facies in a regional if not in a local sense. Herein are observed conditions favorable to the development of effective differentials in static stress and circular shear of the competent cover, and many of the coastal domes exhibit precisely the characters to be expected under such conditions, the Hockley dome being the outstanding example. This stock, plotted 3 miles high with similar vertical and horizontal scales, appears as a low flat table, twice as broad as it is high; surmounting it is a thin but very uniform stratum of anhydrite, grading at the top into limestone, together about 850 feet thick. In area it covers about 25 square miles. It is difficult to visualize this dome or salt stock as having issued through a linear fracture in the competent horizon.

It would be unreasonable to say that dynamic stresses have not been present in any of the coastal domes. Probably dynamic stress has played some part in all of them, but at Hockley and similar domes static stress certainly has been far the more important factor. It also may be said that tangential faulting, as illustrated in the interior domes, is essentially absent, in the surface horizons at least, from the coastal domes. This statement does not include radial faulting, which is more or less well marked around every closely drilled dome, whether interior or other.

The depth of burial of the competent cap sequence cover, in general, makes tangential faulting in that bed difficult to discover. If present, the salt issuing through the fracture, as in the interior domes, should give rise to a rather straight linear arrangement of the domes. Efforts to discover regional faults or fractures in the Coastal basin by seeking a straight line net of the coastal domes have not met with great success. The outstanding exception is observed in the Five Islands line, in Louisiana. The existence of a fault or fracture here can be demonstrated fairly securely on independent evidence, which, however, need not be reviewed here. In connection with the fracture, note the significant fact that caps are practically absent from the Five Islands domes. Cap rock is known only in the northernmost and southernmost domes, Jefferson Island and Belle Isle, respectively, and in these two the cap is not at the top but hangs on a shoulder of salt approximately 1,200 feet down the side. This relation has been interpreted to indicate escape of the salt around one edge of the cap and subsequent rise of the salt "spine." An alternative explanation

is that initial issue of salt through the original fracture was followed by enlargement of the opening through detachment of a portion of the cap layer, which adhered to the enlarged stock with further rise. This explanation has the advantage that these relations are displayed only by the domes at the ends of the line, where the opening of the original fracture supposedly should be least and opportunity greater for enlargement of the opening through further fracture of the competent covering bed. Furthermore, careful distinction must be made between "flowage" of the salt, that is, molecular rearrangement or gliding, and movement of the salt en masse. Flowage occurs in the vicinity of the opening through which the salt issues from the "mother" salt bed; once past this point, the enormous differential stress causing flowage is relieved, and upward movement through the unconsolidated incompetent covering takes place en masse. With the cap shoulders at Jefferson Island and Belle Isle hardly 1,200 feet from the surface and completely enclosed in incompetent material under a pressure which here is relatively slight and is hydrostatic, it is difficult to understand how separate "flowage" of the salt into a spine can be effected.

Between these two extremes—the Five Islands on the one hand and the Hockley dome on the other—the Gulf Coastal basin exhibits domes with all intermediate characters. In many cases it is impossible to say whether the initial fracturing of the competent cover was due to predominant static or dynamic differentials, and distortion and shearing of the cap during upward movement have added to the confusion. Certainly it may be said that in every case a differential was present, no matter what its predominant type, else no dome could have formed.

In the foregoing brief analysis of doming mechanics will be seen further evidence in support of the middle to late Upper Cretaceous age of the salt. The predominant influence of differential static stress in the characters of the Hockley and similar domes is hardly open to question. Were the salt here at the same horizon as that in the interior domes, the competent Glen Rose, Fredericksburg, Washita, and Gulf horizons would far exceed in resistance such static differential stresses as could accumulate in a 10,000–15,000-foot deltaic pile.

6. *Climate criteria.*—Discussion of climatic influences bearing on the middle to late Upper Cretaceous age of the Gulf Coastal salt must refer to two distinct phases of the question. 1. Were physiographic conditions toward the conclusion of the Cretaceous period favorable to the desiccation of the Gulf of Mexico as delimited at that time? 2. What evidence do the Upper Cretaceous sediments themselves supply regarding temperature and moisture conditions at the time of their accumulation?

1. If the present relations of land and sea, and the present atmospheric circulation (planetary and cyclonic), prevailing in the Gulf of Mexico area are postulated as those of the Upper Cretaceous, it may be said that desiccation under such conditions is improbable, in view of narrow land connections between Cuba and Florida and Cuba and Yucatan. Also, it is quite unlikely that the planetary circulation of Upper Cretaceous time was essentially different from that of today. In this respect the probable heights of the Jurassic mountains in Mexico and the rising Rocky Mountains farther north could have exercised an effective drying influence on the prevailing westerlies, but the southeast trade winds, under present conditions, have neither wide nor high lands to cross. Whether the habits of cyclonic winds were the same in Upper Cretaceous time as now is difficult to say; it is probable, however, that desiccation and salt formation requiring a hundred or more thousands of years came about through the chief influence of the steady planetary circulation, and that the effects of the temperamental cyclonic winds were relatively unimportant, whatever the age of the salt.

Thus the question of Upper Cretaceous Gulf desiccation hangs, from a physiographic standpoint, on the restoration of the then prevailing land and sea relations on the eastern and southern sides of the basin.

Geologists have long accepted as a fact the existence of an old land in the region of the Greater Antilles, the Bahamas, and southern Florida. The origin of this land is, however, shrouded in deepest mystery and may go back to Proterozoic time . . . though this old complex is held to be certainly as old as the Permian.[65] . . . The Greater Antilles, Cuba, San Domingo, and Porto Rico appear to have been large land areas during the earlier Eocene, and it further seems that Cuba was then connected with Central America.

Fragmentation of this old land took place in post-Cretaceous time, except for an evident pre-Eocene folding of Upper Cretaceous strata in Cuba. From the apparent size of this old land it may be inferred as possible that the southeast trade winds were deprived of much of their moisture before reaching the Gulf basin, and that the Gulf basin was considerably smaller than indicated by its present shores. These conditions, however, prevailed all through the Mesozoic, and place little accent on any particular time within that interval as a time of salt formation, except for the late Cretaceous folding in Cuba just mentioned. It may be said, too, that the world-wide later Upper Cretaceous sea retreat increased the effective height of the bordering old

[65] Charles Schuchert, *A Textbook of Geology*. Part II, *Historical Geology*, 2d rev. ed. (1924), pp. 570 and 595.

land on the south and east, thus placing some emphasis on this as a probable time of salt formation.

2. Considering evidence of temperature and moisture in the sediments themselves, two antithetical and extreme sets of conditions may be visualized—a climate so warm and arid that there is no precipitation whatever, in which case there is no vegetation and no rivers enter the sea; and a climate, temperate to warm, but so moist that vegetation is luxuriant and the seashore is a succession of rivers, large and closely spaced. Transgression of the sea may be postulated as independent of the climate (excluding the influence of changing glacial climates). In the first case the basal sands of a transgression will be typical marine sands, evenly bedded, well sorted, finely laminated, generally of a light color, and they will be free of lignitic inclusions and deltaic characters. In the second case the basal sands have had small opportunity for marine sorting; they will be thick and poorly bedded; they will display deltaic characters throughout, and will enclose an abundance of lignites.

From the characters of the basal sands the climatic conditions of these two extremes can be read with facility, and between the two all gradations can be deciphered almost with equal ease. The basal sands of the early Comanche in the Gulf Coast are well toward the arid extreme, while those of the Lower Eocene (Wilcox) present the extreme of the second case. Intermediate between the two are the basal sands of the Gulf series. The Woodbine is scatteringly lignitiferous and displays some deltaic markings. The Eutaw in Alabama likewise carries some lignites, and rests on continental (Tuscaloosa) sediments which also are sparingly lignitiferous.

From these considerations the climate of the Gulf Coast during Upper Cretaceous times can be described with considerable confidence as temperate to warm, and neither arid nor moist, semi-arid. It may be said that extreme aridity and warmth are most favorable to desiccation and salt formation, and that a moist climate is unfavorable, but where the line can be drawn between possible and impossible can not be prescribed. The Lower Comanche certainly was a time favorable to marine salt formation, as evidenced by its basal sands, but it can not be said that the Upper Cretaceous time was unfavorable.

In this impassé the freshening effect again plays an important part. With a climate devoid of moisture and land drainage, desiccation and intra-retreat of the land-locked arm of the sea can not be accompanied by zonary salt effects other than Usiglio's sequence, for there is no freshening effect around the shores. On the other hand, the thickness and perfection of development of the salt-cap-rock sequence is in it-

self proof of a marked freshening effect, and it agrees with the foregoing description of semi-arid climate evidenced in the Woodbine and Eutaw. Probably nowhere else in the world is the freshening principle so well displayed as it is in the Gulf Coast, and in it, again, there is evidence of an Upper Cretaceous age for the Coastal salt, for the evidence of marked aridity in the basal Comanche sediments is not in harmony with the highly perfect cap (freshening) sequence found above many of the Gulf Coastal domes.

7. The European or standard section of the Comanche and Cretaceous seems to be fully represented in the stratigraphy of the Gulf Coastal Plain, with the exception of the Danian stage, the last stage of the Cretaceous. Aside from the Cannonball[66] member of the Lance formation, no marine equivalent for the Danian stage is known in North America. The middle to late Upper Cretaceous age of the Gulf Coastal salt completes the standard stratigraphic section and history through that interval in the Gulf Border province. Including as it does the Danian stage, the salt and its cap sequence continued to precipitate until the rising external waters of the lowest Tertiary found their way into the Gulf Basin, which, then refreshed and filled, became again a normal sea.

DISCUSSION

DONALD C. BARTON, Houston, Texas (written discussion received, July 28, 1934): The writer's dissent from this paper is so extensive that in the brief space available for this discussion, it is possible to express only his opinion that the conclusions in the paper represent an interesting, ingenious, but highly improbable hypothesis, and to present sketchy criticism.

Much fundamental argument in this paper is based on strained or erroneous interpretation of data.

1. The marl of late Navarro age in the cap of the South Liberty dome is taken as proving the Navarro age of the cap (p. 1276).

The belief that the Navarro marl was picked up by the cap in its intrusion through the Navarro and that the present inclusion of that Navarro marl in the cap indicates definitely a pre-Navarro age for the salt and at least part of the cap at South Liberty is held unanimously by colleagues of the present writer, such as Weaver, Hanna, Teas, Rolshausen, and Morrison, with whom he has discussed the matter. The mechanics of the inclusions of fragments of the country rock in the edge of the cap are easy. The inclusion of material from the country rock of different ages in the cap is a well established phenomenon. The well in which the Navarro marl was found is on the steeply dipping flank of the dome where the dip of the edge of the flank is approximately 80°. It is slightly more than 1,000 feet down the flank from the shoulder between the flank and the top of the cap; and it is on the upthrown side

[66] T. W. Stanton, "The Fauna of the Cannonball Marine Member of the Lance Formation," *U.S. Geol. Survey Prof. Paper 128-A* (1921). H. W. Shimer, oral communication.

and close to a rather considerable radial fault on the cap rock. The explanation of inclusion of a mass of Navarro marl in the edge of a pre-existing cap as it pierced the Navarro formation is so simple and so in conformity with what we know of the behavior of salt domes that no justification seems to be present for so strained an interpretation as that this Navarro marl is indigenous to the cap. It may be indigenous to the cap in the sense that the cap is not all of one age but picks up and includes in itself extraneous material during the course of its upward intrusion. In that sense the Navarro marl might be spoken of as part of the cap, but would carry no connotation in Brown's sense that the cap had formed in Navarro time: the connotation would be that the cap and salt would be at least as old as Navarro, and presumably pre-Navarro. Morrison explains[67] that his statement on which Brown depends so strongly meant only that the marl is to-day a physical part of the cap rock mass; he tends toward the accretionary theory of the cap; and in that sense that marl would be an indigenous part of the cap; but the cap then would be of many ages. Morrison believes that the salt and at least part of the cap are older than Navarro, and that they picked up the Navarro marl during their intrusion through that formation.

2. In connection with the Boggy Creek salt dome (p. 1272): The statements are made: (1) that

> The fact, however, that the anhydrite [of the cap] underlies definitely identified Glen Rose makes it thoroughly reasonable to correlate this anhydrite with the bed [of sedimentary anhydrite] underlying upper Glen Rose farther northeast in the basin on the flank of the Sabine arch;

and (2) that

> Since... uplift of the dome has not greatly disturbed the stratigraphic succession, it is reasonable to conclude that the Boggy Creek section represents the normal saline sequence, according to which the salt should underlie the anhydrite and be itself underlain by lower Glen Rose limestone . . . but if later work discloses the limestone above the anhydrite to be upper Glen Rose, and the lower Glen Rose to be absent above the dome, this point may be regarded as proved.

Correlation of the cap-rock anhydrite with the known Glen Rose simply because Glen Rose lies on the anhydrite of the cap does not seem justified. That relation would be entirely normal, if the salt and cap are older than Glen Rose. The megascopic character of the cap-rock anhydrite is remarkably constant throughout the coastal and interior domes and is quite dissimilar to the megascopic character of the Glen Rose anhydrite. Anhydrite cap rock which megascopically resembles some of the Glen Rose anhydrite has been encountered on the Garden Island dome at the top of the Mississippi delta, but no other similar occurrence is known to the writer or to the Humble Paleontological Laboratory. The known data are insufficient to show that the cap-rock anhydrite can not be Glen Rose anhydrite which has been altered during the upward intrusion of the dome. We may not deny to a geologist the surmise that the cap-rock anhydrite at Boggy Creek is of Glen Rose age. But on the present knowledge of the data, the weight of the evidence would seem to be slightly against that correlation; and certainly, there is no question of its being "thoroughly reasonable" to correlate the Boggy Creek anhydrite with the Glen Rose anhydrite.

[67] Oral communication, June 6, 1934; wording of statement checked and approved by Morrison.

The succession—upper Glen Rose (lower Glen Rose limestone missing), cap-rock anhydrite, salt—and the slight disturbance of the stratigraphic succession within the range of the present drilling would be entirely normal, if the salt is pre-Cretaceous. At least, a similar situation is quite normal for the domes of the coastal group; and no reason is known to the writer why it should not be normal for East Texas domes of pre-Cretaceous salt. Certainly valid evidence must be adduced to demonstrate that the succession at Boggy Creek and the slight disturbance of the stratigraphic succession is improbable if the salt is pre-Cretaceous; otherwise the presumption must be in favor of their probable normality. A geologist may not be denied his right to surmise that the succession at Boggy Creek is the normal saline succession, but certainly it is not "reasonable to conclude" that the Boggy Creek section represents the normal saline sequence, nor may "this point be regarded as proved" if the lower Glen Rose limestone is found to be absent over the dome.

3. "Another feature evidencing the separate character of the Smackover basin is seen in the great thickness of the salt" (pp. 1262–63).

If we assume for argument that the great thickness of the salt is not due to a salt dome, it is difficult to see why great thickness of the salt indicates a separate basin. Positively nothing is known about the thickness of the mother salt stratum in North Louisiana or East Texas. A continuous sheet of salt 1,100 feet thick from Smackover into the northern Louisiana salt-dome area is wholly within geologic plausibility. Greatest thickness of the salt at the northern end, at Smackover, would be possible and would be congruent with the formation of the salt domes as we know them in northern Louisiana. Without further explanation, which is not given, it is not evident how the thickness of the salt gives any evidence one way or another in regard to the presence of a separate Smackover basin.

4. The argument for the impossibility of a salt dome at Smackover is not convincing (pp. 1262–63). We do not know enough about the deep geology of southern Arkansas to postulate the improbability, much less the impossibility, of 5,000 feet of beds below the Lower Trinity marine series at Smackover. Deep drilling has shown very much more surprising and more unexpected features, for example, the deep Paleozoic trough between the Llano-Burnet uplift and the edge of the Upper Cretaceous. The structural contours on the oil sand at Smackover show two sub-circular domes with a saddle between. The form of the domes is congruent with the presence of twin salt domes. The salt well is correctly located on one of the domes for the salt to be part of the salt core. The data are insufficient to prove or disprove the presence of a salt dome at Smackover, but the writer's surmise (55/45) is in favor of the presence of a salt dome.

It should be noted, furthermore, that pre-Comanche doming, erosion down to the salt, and absence of doming during the Comanche, is entirely compatible with our present knowledge of the behavior of salt domes; and that on the basis of the single well into the salt, it is impossible to prove whether the contact between the salt and the overlying Lower Trinity marine series is conformable, unconformable, or intrusive.

5. The use of the east-west gravity-maximum ridge which the writer showed in a regional gravity map seems to him nicely characteristic of the use of the data in this whole paper. The gravity ridge was not discussed in the paper by the writer and his associates. The writer has many thousand

per cent more information about the gravity ridge than he published. He has been looking at it for 4 or 5 years, but he does not yet think that he knows enough about it for him safely to make a public interpretation of it. The idea of a buried ridge of course occurred to him, but there is a considerable array of difficulties yet to be explained before that explanation of it can be supported. The writer, furthermore, is not sure that the regional coastal trough of minimum does not connect with the East Texas minimum through Washington and Grimes counties. The Pine Prairie dome (proved salt dome), Livingston dome (salt definitely indicated by the torsion balance), the Spurger dome (salt suggested but not definitely indicated by the torsion balance), lie within this gravity ridge, and, therefore, vitiate Brown's argument from the gravity ridge of maximum.

The problem of the origin of salt deposits needs extensive consideration. The conditions under which a thick salt deposit will form must be decidedly special. A basin 1,000 feet or more deep must be present; or tectonic conditions must be such that enough deposition can take place to initiate isostatic subsidence to keep pace with the deposition of the salt; or a negative tendency must be present over the area of what is to be the salt basin. But simple regression of the sea seemingly should not leave favorable basins along a coastal plain shore like that of the Gulf Coast; although it might do so along a coast like that of California. Rather, preceding or concomitant deformation would seem also necessary to cut off large arms of the sea. Such deformation might produce no change in sea level and yet produce the requisite conditions for the conventional "bar theory" of salt deposits and a change of only a few feet in the water level of the enclosed arm of the sea. The regression series of Brown's paper would not form, although salt deposits might. If the regression of the sea is produced by uplift, a deep enough basin must be present so that either a thick salt deposit can form without diastrophism or that the deposition of a relatively thin salt deposit can overcome the positive tendency and produce isostatic subsidence of the basin.

Certain meteorological-geographical conditions, furthermore, must be met to produce the requisite aridity for the formation of salt deposits. Aridity is produced: (1) in the lee of mountains across the path of the moisture-bearing winds; the moisture is precipitated on the windward side, and the descending winds blowing down from the mountain range are intensely drying; (2) where the sub-tropical high pressure zones cross the lands; and (3) to a lesser extent where trade winds have blown for a long distance across land. On-shore trade winds normally are moisture bearing and moisture precipitating. It is a grave question, therefore, whether it is meteorologically permissible to postulate aridity along the Louisiana-southeast Texas gulf shore during Navarro time.

The question of non-marine salt deposits deserves further consideration. Great Salt Lake gives a small example of the formation of non-marine salt deposits, and the writer does not understand that the regression sequence is present, or is likely to form. Or further, it takes little geologic imagination to envisage a mountain range damming the Nile back into the Sahara; it would then be possible for a large and thick salt deposit to form. A somewhat similar situation can be envisaged for the Gulf Coast area. Land extending across the present Gulf area of the United States to South America and Central America, and Cuba as is postulated by some geologists for the end of the

Paleozoic and beginning of the Mesozoic, would most probably produce aridity in the Texas-Louisiana salt-dome areas. Drainage from the north and east might be dammed up in the Gulf Coast area to form a large continental salt lake, in which thick salt deposits might form, without the regressional sequence.

Several plausible alternative theories of the origin of thick salt deposits, therefore, can easily be envisaged and from brief consideration seem plausible, although it is of course possible that more detailed study of the problem might disprove the probability of one or more of them. Brown's paper seems to assume that thick salt deposits must form only in the regressional sequence, for no discussion is given of other possible conditions of the formation of thick salt deposits, and part of the basic argument of the paper is vitally dependent on the necessity of the Texas-Louisiana salt-dome deposits being part of a regressional sequence.

The conclusion that the salt of the Smackover, East Texas, and northern Louisiana areas (pp. 1270–74), can not be of pre-Comanche age is rather vital to much of the further argument in regard to the age of the salt, for Brown argues that the Sabine uplift and the ridge separating the Smackover and northern Louisiana basins are pre-Comanche and that the salt, not being pre-Comanche, must be younger than the ridges and, therefore, must have formed in separate basins.

The conclusion of the impossibility of the pre-Comanche age of that salt is based largely on the two postulates: (1) that those salt deposits must have formed as part of a regressional sequence and, therefore, must have been accompanied by very thick and far-flung sediments of a border facies; and (2) that the absence of Permian Jurassic beds of border facies precludes a Permian-to-Jurassic age of the salt.

The weakness of the first postulate has been covered in preceding paragraphs. Until proof of the contrary is built up, thick salt deposits must be regarded as being possibly of more than one type of origin. The succession at Smackover, which is compatible with the position of the salt in a Trinity regression sequence, is not proof of that position of the salt, for the sequence is equally compatible with the position of the salt in an intrusive salt dome core.

The second postulate also is open to question. The absence of Permian, Triassic, and Jurassic sediments in the wells which have gone through the Comanche is of course weak evidence of the actual absence of those deposits throughout the whole general area. That evidence would seem to the writer to justify a tentative surmise or a tentative alternative hypothesis, but it would seem very dangerous to place too much dependence on such evidence. Wells have gone through the base of the Comanche into Pennsylvanian or older rocks only around the peripheries, essentially only around the west and northwest periphery of the salt basin, or group of basins. The area over which no well has reached the base of the Comanche is wide and extensive and wholly unbounded on the south. Deep drilling through a cover of sediments has brought so many discoveries of unsurmised geologic features that it seems dangerous to make any strong postulate that Permian, Triassic, or Jurassic beds were never deposited, or that having been deposited over a wider area than they now occupy in the depths of the basin, or basins, they were not eroded from the periphery, where the wells now reach the pre-Permian.

The corollary then follows that if the salt and the barrier ridges between the salt basins all are pre-Comanche, the question of relative age of the salt and of the ridges is left open. As a matter of fact, the basement rock of the Sabine uplift has not been drilled into and we do not know that the salt does not extend across its crest, and similarly, for the area between the Smackover and northern Louisiana basins. If drilling shows that the salt does not extend across those inter-salt-dome ridges, it would still remain an open question whether the salt beds had never been deposited in those areas, or had been eroded as the Zechstein salt deposits have been eroded from across the Harz uplift.

Severe dissent must be expressed to the conclusion (pp. 1259–60) that

> Thus the form and structure of the Coastal Plain sediments clearly reflect a buried ridge trending east-northeast across the Mississippi embayment south of the Texas and Louisiana interior basins, and underlying the Coastal barren belt.

The gravity high which was discussed in a previous paragraph does suggest the possible presence of an old land mass between the East Texas and North Louisiana basins, and the Gulf Coast geosyncline, but as the writer stated in that discussion, he does not yet feel that it is safe to interpret that high as indicating a buried ridge. It is difficult to see how the rest of the argument leads at all to the conclusion of the presence of any such buried ridge. The evidence which is adduced can all be explained simply in other ways. For example: the East Texas basin is enclosed on three sides; and an important aquifer, the Woodbine sand, lenses out toward the south. Artesian conditions would seem normal; and the fracturing around the salt domes might be expected to conduct some water to the surface, and produce the springs which are mentioned in the paper. Discussion in United States Geodetic Survey Water-Supply Paper 335 does not give any indication or suggestion of barren artesian conditions in Brown's barren zone between the East Texas salt basin and the coastal dome area. In the Gulf Coast proper, the rather general, but not complete, absence of springs around domes is easily explained by the presence of the thick massive plastic gumbos which are not present in East Texas.

Severe dissent must be expressed to the conclusion of the Navarro age of the salt of the Gulf Coast area (pp. 1274–83). It is wholly impossible for the writer to follow Brown's argument to his conclusion. He presents no evidence that the salt can not be pre-Navarro. He is not consistent in his argument in regard to the significance of the absence of his border facies, for he takes the absence of Permian, Triassic, or Jurassic sediments of the border facies as strong evidence of the impossibility of a Permian-to-Jurassic age of the salt; but the absence of Navarro sediments of border facies is not taken as evidence of the impossibility of a Navarro age. It is impossible to see how the evidence which he presents indicates a Navarro age of the salt; and the Navarro on the South Liberty dome, to the writer, is decisive evidence that the salt must be of pre-Navarro age.

The writer, in conclusion, does not wish to be understood as arguing that the salt is pre-Comanche, that it can not have been deposited in separate basins, that the salt in the different basins can not be of different ages, that the ridge under the barren zone does not exist. He wishes merely to argue: (1) that Brown's contention in regard to those questions is decidedly inconclusive; and (2) that final conclusions are justified no further than that

the Smackover salt is at least as old as lowermost Trinity, that is, older than the Lower Trinity marine series, that the East Texas salt is pre-Glen Rose, and that the Gulf Coast salt is pre-Navarro. He surmises that the salt is all of one age and, therefore, at least as old as basal Trinity in age; but he recognizes that as a surmise and not as a proved, or semi-proved, fact. He is not hostile to the idea of the buried ridge, but he rates it as an alternative hypothesis which as yet can not be proved or disproved.

The writer would be more charitable toward this paper if it were labelled as a speculation, for it is an intriguing, although far-fetched, speculation, but the idea and evidence submitted in the paper are labelled as definitely or highly conclusive:

(1255) . . . the writer has noted many features of the salt domes . . . which clearly indicate the salt in the several areas to be of different ages.
(1259–60) Thus, the form and structure of the Coastal Plain sediments clearly reflect a buried ridge . . . .
(1269) . . . it may be concluded with high confidence that the Gulf Coastal salt can not be older than the Comanche.
(1270) Proof that . . . seems to fix the age of the Smackover salt rather definitely.

W. C. SPOONER, Shreveport, Louisiana (written discussion received, August 9, 1934): In part II of this paper the following conclusions are stated: (1) that the Smackover, Louisiana interior, and Texas interior salt areas are segregated areas of salt occurrences and separate and distinct basins of salt deposition, and (2) that the salt in the Smackover area is lowest lower Trinity in age and in the Louisiana and Texas interior area the salt is middle Glen Rose in age.

It is the writer's opinion that these conclusions are in error and it is the purpose of this discussion to outline briefly the evidence on which that opinion is based.

The basin in which the Comanche sediments accumulated was essentially continuous across East Texas, southern Arkansas, and northern Louisiana, at least as far east as the southeastern corner of Arkansas and the northeastern corner of Louisiana. The continuity of the Trinity basin of deposition is amply demonstrated by the records of numerous deep wells drilled within this region.

The Trinity group as developed in deep wells in this region is divided as follows.

Trinity group	*Maximum Thickness (Feet)*
Upper Glen Rose	1,700
Anhydrite member	600
Lower Glen Rose	1,100
Trinity red beds	2,100
Neocomian?	
Limestone, shales and sands	1,600+

The upper Glen Rose includes the equivalent of the Paluxy sand marking a gulfward regression of the Trinity sea. In northwestern Louisiana and the adjacent parts of Texas the southern limits of the Paluxy (red shale and sands) are in the latitude of the Elm Grove field, approximately 125 miles south of the outcrop. South of this line the upper Glen Rose consists of marine shales and limestones.

FIG. 8.—Diagrammatic section of Trinity group through southwestern Arkansas and northwestern Louisiana.

The Anhydrite member of the Glen Rose is made up of anhydrite interbedded with marine shales and limestones and attains a maximum thickness of 600 feet in northeastern Louisiana and the adjacent part of Texas. This member decreases in thickness towards the margin of the basin and gulfward, with the belt of maximum thickness parallel with the margin of the basin.

The lower Glen Rose consists of marine shales and limestone which attain a thickness of 1,100 feet in northern Louisiana and east Texas. Toward the north and northeast (toward the margin of the basin) it decreases in thickness and interfingers with red shales and sands; toward the south, or basinward, it likewise decreases in thickness to 600 feet in Sabine Parish, Louisiana, approximately 175 miles south of the outcrop.

The Trinity red beds, consisting of red clays, shales, and sands, attain a maximum thickness in northern Louisiana and southern Arkansas of 2,100 feet but decrease in thickness basinward and in Sabine Parish, Louisiana, are represented by non-red shales of undetermined thickness.

Below the Trinity red beds lie a series of marine shales, limestones, and sands of undetermined thickness, but penetrated to a depth of 1,600 feet in northern Louisiana. These beds, although not definitely correlated, are believed to be Neocomian in age.

The accompanying illustration (Fig. 8) represents a section of the Trinity group transverse to the margin of the basin which in this particular section extends north and south. The relationship of the anhydrite member to the Glen Rose above and below and to the Trinity as a unit fails to indicate that this member is related to salt deposition, but, on the contrary, strongly suggests sedimentary environmental conditions favorable to the precipitation of anhydrite without desiccation. As indicated in the accompanying section, a trench-like depression existed parallel with the margin of the basin of deposition during the deposition of the anhydrite as well as the older Trinity sediments. Toward the end of the lower Glen Rose this part of the basin was shallow, as indicated by the oölitic structure of much of the limestone; a minimum of sedimentary material was received, but the waters emptying into the basin appear to have carried a high percentage of salts in solution which, through environmental conditions other than desiccation, were precipitated to form the anhydrite and associated limestone precipitates.

Sections drawn from northeastern Louisiana southwestward through the Louisiana interior salt-dome area, and from north to south in Texas, passing through the

Van field, Van Zandt County, would not differ in important essentials from the section shown in the accompanying illustration, indicating the continuity of the basin throughout that distance.

The evidence does not support the conclusion that the salts in the Texas and Louisiana interior areas are middle lower Glen Rose in age, but on the contrary suggest that the salt is older than, and certainly as old as, the Neocomian, and probably older than the Lower Cretaceous.

There is no evidence in support of the conclusion that the salt in the Smackover well is older than in the Louisiana interior salt-dome areas; the Trinity sediments are continuous into the Smackover area without any, excepting nominal, changes as the margin of the basin is approached. The Louisiana interior salt area is furthermore not limited to the area of penetration type of domes, as geophysical data indicate that a number of structural features, such as Cotton Valley, Homer, Haynesville, Bellevue, and the Pine Island domes, are the result of salt movements at depth. It is also indicated that the Elm Grove and Sligo fields may owe their structure to salt movement. It is therefore evident that salt must have been deposited over at least a part of the Sabine uplift. The Homer dome is not more than 50 miles from the deep Smackover well. It is the writer's opinion that the salt deposits in the interior salt-dome area are continuous with the Smackover area.

The continuity of the Arkansas and Louisiana salt deposits with the salt in the Texas interior salt area is problematical.

The deep wells in Arkansas listed by Miser and Sellards[68] are only a few of the deep wells which have penetrated the pre-Cretaceous rocks. The dip of the basement floor is nominal, 100–150 feet per mile from the Coastal Plain margin basinward for some miles where the moderate dip is interrupted by a sharp flexure, beyond which the dip is more than doubled and even trebled. It is furthermore shown that the rocks encountered in some of these deep wells are not typical of the Ouachita Mountain sediments. As an illustration, the following wells serve the purpose of pointing out this fact. The Pure Oil Company's Moline Timber Company well No. 1, Sec. 21, T. 11 S., R. 17 W., drilled principally very hard, fine-grained sandstone from 2,425 to the bottom of the hole at 2,885 feet. This section, which was non-fossiliferous, was entirely distinct in lithologic character from any Trinity rocks recorded or observed. The Dickson *et al.* Benton Heirs well No. 1 in Sec. 24, T. 12 S., R. 19 W., encountered the base of the Trinity at 2,630 feet, and from 2,630 to 2,920 feet principally sandstone with subordinate beds of shale and thin lenses of red shales were recorded. From 2,920 to 3,205 feet, gypsum, red beds, and coral rock were recorded; and from 3,205 feet to the bottom of the hole, at 3,550 feet, limestone was recorded. The driller described a part of the gypsum as crystalline. Sufficient material is not available from this well to determine its age, but it seems probable that the lower part may have consisted of limestone and anhydrite. These rocks, also encountered in other wells, have no counterpart in the Ouachita Mountains.

The existence of a basin in this region prior to Trinity time is not only probable but appears to be a plausible conclusion, and the fact that rocks younger than Pennsylvanian are not found along the margin is not surprising in view of the deformation history of the region, where, as late as at the end

[68] H. D. Miser and E. H. Sellards, "Pre-Cretaceous Rock Found in Wells in the Gulf Coastal Plain South of Ouachita Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 7 (July, 1931), pp. 801–18.

of the Comanche, there was sufficient uplift along a southeasterly trend through southeastern Arkansas and northeastern Louisiana, followed by an interval of erosion, to remove more than 3,000 feet of Comanche sediments, followed by complete overlap of the Upper Cretaceous. The interval between the Ouachita Mountain orogeny and the beginning of the Comanche epoch represents a long time interval during which both sedimentation and erosion could have operated to complicate the geologic history. The comparison of this region with the West Texas region in relation to Permian, Jurassic, and Triassic history would be even less revealing than a comparison of the Comanche history of these regions.

DISCUSSION

LEVI S. BROWN (written discussion received, August 29, 1934): I wish to tender my thanks to the *Bulletin* for publication of this lengthy paper, and to the reader for his attention to the new arguments and views presented. Without further burden to either, I request but a few words in conclusion.

After a broad study of cap rock, chiefly petrographic, I summarized my observations in a paper published by the *Bulletin* in May, 1931. The evidence recorded there led me firmly to the conclusion that the cap rock represents a fragment of a sedimentary bed above the salt. For me, that part of the question was settled, and the next phase of the problem became a search for the method or process, then unknown, by which such a sedimentary succession could be established.

A beaker or evaporating dish may be filled with sea water and evaporated to dryness. Successive cross sections of the system may be drawn, showing the situation, surfaces, and interrelations of the several salts as they are developed in the evaporative process, to its termination. Envisioning a natural basin, such as the German Zechstein, or the North American Gulf Coast, 600–800 miles in diameter, and 2–3 miles in depth, let an attempt be made to draw successive cross sections showing the interrelations of all salts formed at successive stages in the evaporative process as it takes place in nature. No such detailed restoration is available in the literature. Such an attempt is not speculation, but is deductive reasoning from established principles and natural phenomena. In this attempt I found what is to me the explanation of the origin of cap rock, as described briefly in the present paper.

Analysis of Gulf Coastal sedimentation, in the light of the conclusions reached in this attempt at detailed restoration, leads to other interesting observations, previously set forth. This analysis was written and sent to the *Bulletin* in June, 1933, with some trepidation because of a lack of knowledge or access to information concerning the regional geophysics of the Gulf Coastal Plain, recognized as a serious deficiency at the time. Several months later, in September, 1933, the *Bulletin* published Barton's paper on the Gulf Coast geosyncline, accompanied by a regional geophysical map. That my sedimentational analysis had placed an elongate deeply buried ridge in precisely the same situation that Barton's map indicated a regional gravity "high" is neither accident nor coincidence. Rather, I regard it as testimony to the value of my reasoning.

Lastly, no trace of offense is intended in the style of writing, which is none the less of deliberate adoption. To me, geologic literature is overfull of the

inconclusive,—surmise and conjecture. It may be, and has been, argued that geology belongs to the so-called "inexact" sciences, but I believe rather that we have not become familiar with the exactness of many natural processes. In this connection I would like to ask Mr. Spooner to detail a clear picture of the "environmental conditions other than desiccation" (that is, excess evaporation) that could cause the precipitation of heavy limestone and calcium sulphate formations. Discovery of this exactness, with reference to saline formations in large basins, is the prime objective of this paper. No one but myself is committed to the conclusions presented, but I am sufficiently sure of these to venture submitting them in public for wider consideration.

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ANHYDRITE-GYPSUM PROBLEM OF BLAINE FORMATION, OKLAHOMA[1]

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ABSTRACT

The three gypsum and anhydrite beds of the Blaine formation, the Medicine Lodge, Shimer, and Lovedale, respectively, which crop out at Salt Creek Canyon, Blaine County, Oklahoma, the type locality of the Blaine, were studied for the purpose of determining their origin and relationships.

Field studies were made of this area and samples were collected from each of the anhydrite and gypsum beds. Detailed megascopic, microscopic, microchemical, and petrographic examinations were made of the samples to determine their genetic relationships.

These investigations disclosed that the anhydrite, in radial form, is slowly hydrating to gypsum. No evidence of volume change during hydration was found. The conclusions reached as a result of the study are that the gypsum of the area has formed near the surface by the hydration of anhydrite; that there was no increase in volume when this hydration took place, and that the anhydrite probably was the primary precipitate in a desiccation basin, being deposited in a hot and dry climate.

ACKNOWLEDGMENTS

The writer wishes to express his sincere appreciation to G. E. Anderson, who directed this research problem, to C. A. Merritt, Samuel Weidman, and V. E. Monnett, of the geology faculty of the University of Oklahoma, and to R. L. Clifton, of Enid, Oklahoma, for valuable suggestions and criticism. Appreciation is also expressed for financial assistance in the form of a research fellowship.

INTRODUCTION

Many questions concerning the origin of the beds of gypsum and anhydrite of the Permian Red-beds of the Western Interior have arisen. This study has been made to help solve these problems. It is hoped that additional areas can be examined and more information accumulated in regard to the origin of these minerals, for only a small area was covered in this investigation.

Salt Creek Canyon, the type locality of the Blaine formation (8),[3]

[1] Presented by title before the Association at the Dallas meeting, March 24, 1934. Manuscript received, February 17; revised manuscript, July 24, 1934. Abstract of part of research problem and thesis submitted in partial fulfillment of the degree of Master of Science at the University of Oklahoma, Spring, 1933.

[2] 1105 East Maple.

[3] This and the following references are in the reference bibliography at the end of this article.

was chosen for field and laboratory studies, because of the good exposures of gypsum and anhydrite found there. The canyon is about 1.5 miles south and 1 mile east of Southard, Blaine County, Oklahoma, at the headwaters of Salt Creek, a tributary of Cimarron River.

The headwaters of the southeastward flowing tributary streams of the Cimarron have eroded back into the westward dipping beds of the Blaine formation to form a high escarpment in northwestern Oklahoma. Salt Creek has carved one of the deeper niches into the high Blaine escarpment, forming large canyons that branch and extend back into the outcrop nearly 2 miles to the stream head. The stream has eroded through the Blaine outcrop and has exposed a considerable section of the Flowerpot shales, the formation immediately below. The gypsum and anhydrite beds cap the divides and tend to combat the head erosion of the stream, thus creating the large canyons with their steep walls.

Problem of Origin of Anhydrite and Gypsum

Several theories have been advanced for the origin of the large deposits of gypsum and anhydrite found in various parts of the world.

1. Bischof (3) first suggested the bar theory for the primary origin of the Stassfurt saline deposits. This later was worked out in great detail by Ochsenius (15) and has since become the prevailing conception of the origin of all saline deposits. According to Van't Hoff and Weigert (21), who also worked out the relations of the Stassfurt saline deposits in Germany, either anhydrite or gypsum may be precipitated from waters containing chlorides by evaporation in a lagoon or landlocked basin, depending on the temperature. In sea waters, they found anhydrite would be precipitated at temperatures above 25°C., while gypsum would be precipitated at lower temperatures.

2. It is common knowledge that secondary gypsum may be formed by the action of sulphurous acids upon limestone. Dana (5) was one of the early advocates of this explanation for the origin of the New York state deposits. Sherwin (19) suggested that the Oklahoma and Kansas deposits had originated from limestone. The deposits of Nova Scotia and New Brunswick have also been considered of such an origin, but Bailey (1) and Newland (14) now report the gypsum to have been formed by the hydration of anhydrite.

3. Branson (4) modified the bar theory of Ochsenius to include an inner basin, with connecting lagoons, such that the inner one was supplied only with concentrated waters. This modification was made to explain more satisfactorily the absence of fossils and sedimentary im-

purities in gypsum deposits and to account for the great thicknesses of salt and gypsum beds.

4. Grabau (10), following the ideas of Walther (22), held that many salt deposits were of continental origin, the saline minerals having been leached from surface formations by ground water and carried into inland basins where they were deposited by evaporation. Grabau attributes such an origin to the Salina salt series of New York.

5. The well known fact that gypsum may be formed by the hydration of anhydrite led Rogers (18) to the conclusion that most gypsum beds had formed by the alteration of sedimentary beds of anhydrite. Previously, he had assigned such an origin to some of the Kansas gypsum deposits (17). Newland (14) has supported the view of Rogers, pointing out that much anhydrite has been found below the ground-water surface.

6. It is thought by many geologists that gypsum could alter to anhydrite, if sufficient pressure were obtained to squeeze out the water of hydration (2, 14). However, experimental work (13) tends to show that heat rather than pressure is the most important dehydrating factor.

Problem of Volume Change

It has been established by Lindgren (12) that replacement in many mineral deposits takes place volume by volume, that is, without volume change. This has not been applied to the hydration of anhydrite, the common view being that anhydrite replacement by gypsum is molecule by molecule. Since the anhydrite molecule increases its volume when it takes up two molecules of water to form gypsum, a volume increase must take place, if replacement is molecule by molecule. Grimsley (11) claimed this volume increase was 33 per cent, while Grabau (19) and Twenhofel (20) placed it at 50 per cent, and Newland (14), as late as 1929, declared it to be 60 per cent.

Blaine Formation

The Blaine formation emerges from beneath the Comanche and Tertiary overlap in Barber County, southern Kansas, near the town of Medicine Lodge. It swings southeastward, and then west and southwest, around the Anadarko basin in western Oklahoma, and extends into west-central Texas as far south as Concho River, near San Angelo, a linear distance of nearly 600 miles.

The position of the Blaine in the Permian Red-beds of north-central and northwestern Oklahoma is shown in the following section.

Quartermaster	Flowerpot
Cloud Chief	Hennessey
Day Creek	Garber
Whitehorse	Wellington
Dog Creek	Stillwater
Blaine	

The Blaine formation has been divided (7) into the following section at the type locality.

Gypsum (Lovedale)	Dolomite
Dolomite	Shale
Shale	Gypsum (Medicine Lodge)
Gypsum (Shimer)	Dolomite

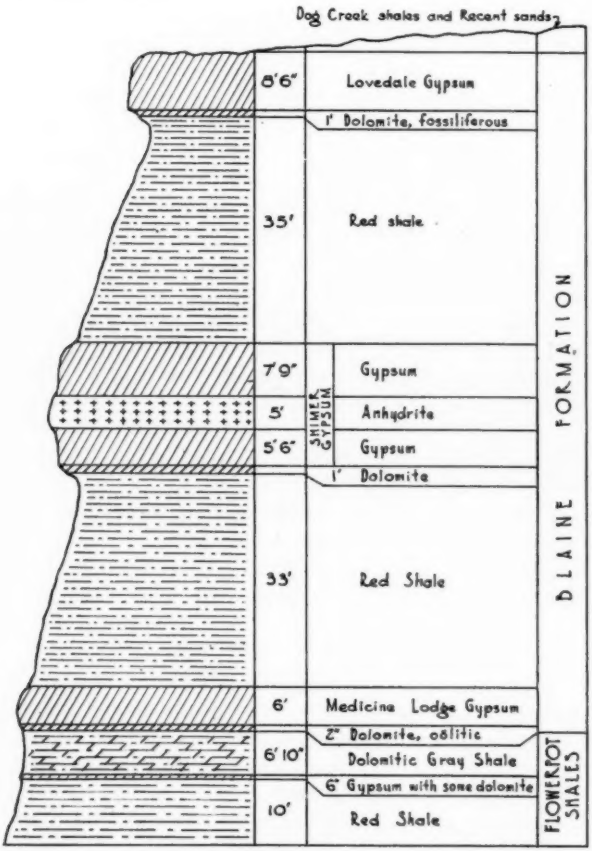

FIG. 1.—Geologic section of Blaine formation at Salt Creek Canyon.

The Blaine rests on the Flowerpot formation, which is composed of red gypsiferous shales, interbedded with thin zones of gray shale (Figs. 1 and 2). Much gypsum is present toward the top of these shales. Every crack and crevice in the shales seems to have been filled with satin spar, thus forming small veinlets of gypsum which intersect in all directions.

Investigation of Problem

Field Work

The dolomite at the base of the Medicine Lodge gypsum is 2 inches thick, very hard, and obscurely laminated. The lower part is oölitic in texture; the upper part is more granular and grades into the gypsum above.

Fig. 2.—Blaine exposure at Salt Creek Canyon. *M:* Medicine Lodge gypsum. *S:* Shimer gypsum. *L:* Lovedale gypsum. *sh:* red shales intervening between gypsum members. *F:* Flowerpot shale below Blaine. *a:* anhydrite boulders, which evidently have broken off of Shimer ledge.

The Medicine Lodge gypsum is 6 feet thick, laminated, and banded throughout. The gypsum at the top and bottom of this bed is rather soft and porous; the center is harder and more compact.

A series of red shales, 33 feet thick, lies on the Medicine Lodge gypsum. These shales have considerable gypsum in cavities and many intersecting satin-spar veinlets.

Above the shales, and separated from them by a sharp contact, is a fairly soft dolomite, one foot thick, light gray in color, granular, and laminated.

The Shimer gypsum lies on the dolomite. It is 18 feet, 3 inches thick, consisting of a lower gypsum bed 5 feet, 6 inches thick, a middle bed of anhydrite 5 feet thick, and an upper gypsum bed 7 feet, 9 inches thick. The anhydrite and gypsum beds show obscure laminations. The uppermost portion of the Shimer gypsum has many solution cavities and is very soft. Normally the anhydrite bed is about 5 feet thick, but it was found to thin to a foot in one place with no apparent reduction in the total thickness (18 feet, 3 inches) of the Shimer gypsum. In another place, the anhydrite is absent, its place being taken by gypsum (Fig. 3), but the total thickness of the Shimer is the same.

FIG. 3.—Anhydrite in Shimer gypsum. Anhydrite pinches out completely (right of center in photograph). Note that lower gypsum-anhydrite contact (marked with black line) cuts across bedding planes of anhydrite. *a:* anhydrite. *lg:* lower gypsum bed. *ug:* upper gypsum bed. *b:* bedding planes in anhydrite. *uc:* upper contact of anhydrite and gypsum. *lc:* lower contact of anhydrite and gypsum.

A large block of anhydrite and gypsum is shown in an upright position in the bottom of the stream (Fig. 4). Note the tongue of anhydrite in the gypsum and the uneven contact line, as well as the small amounts of gypsum along bedding planes and cross fractures.

Another red gypsiferous shale series, 35 feet thick, rests on the Shimer gypsum.

A soft dolomite, one foot thick, and with many solution cavities,

lies on the red shales. Many fossil casts, chiefly pelecypods, are found in the basal part of this dolomite.

FIG. 4.—Large anhydrite and gypsum boulder at bottom of canyon. This boulder evidently broke off of Shimer gypsum ledge. Note anhydrite (*a*) tongue in the gypsum (*g*). Gypsum can be seen along bedding planes (*b*) of anhydrite. Note apparent stratification (*s*) of gypsum parallel with that of anhydrite.

LABORATORY WORK

METHODS

Samples of Blaine gypsum and anhydrite collected at Salt Creek Canyon were given detailed megascopic, microscopic, petrographic, and microchemical examinations. A 25 per cent solution of acetic acid, as used by Merritt in his studies of the Simpson formation (6), was found to be particularly satisfactory in the microchemical tests, for the identification of the small dolomite grains. Colors of each sample

(dry and in the shade) were determined by the use of Ridgeway's *Color Standards and Color Nomenclature* (16).

RESULTS OF STUDY

Medicine Lodge gypsum.—A megascopic examination shows the lower part of this gypsum to be compact and crystalline. The middle part is fine, compact, and crystalline, rather hard, banded, and somewhat laminated at the surface exposures. The upper part is soft, minutely crystalline, massive gypsum, badly weathered, with no apparent bedding. A few laminae of satin-spar ranging from 0.1 inch to 0.125 inch thick occur in this gypsum, the individual crystals being acicular and oriented perpendicular to the bedding of the rock. The color varies from pale smoke-gray to smoke-gray to pale gull-gray.

A microscopic study shows the lower part to be composed of irregular-shaped crystals of gypsum extremely variable in size, ranging from very minute (0.05 millimeter or less) to 5 millimeters in diameter. The gypsum appears fibrous, due to the optical effect of 010 cleavage. Minute cubes and irregular crystals of anhydrite surrounded by single crystals of gypsum are present. A few small crystalline aggregates of anhydrite can be observed radiating from a common center. Some crystalline grains of dolomite are present, ranging in diameter up to 0.5 millimeter. The dolomite gradually decreases in amount upward from the dolomite and gypsum contact.

The middle portion of the bed is composed of much anhydrite, as well as gypsum. The anhydrite occurs in small irregular cubes and in a few small aggregates of crystals radiating from a common center. It has good cleavage, good absorption, and high birefringence. The gypsum ranges in size from large irregular crystals to very small ones. This gypsum surrounds the anhydrite crystals, and is found also along most of the cleavage planes. Definite channels, filled with gypsum, were found extending through the anhydrite. A few scattered dolomite crystals of irregular shape and medium size (about 0.25 millimeter) were found. Also irregular patches and stringy aggregates of iron hydroxide occur.

The upper part of the bed is composed of very fine irregular-grained gypsum with a few larger fibrous anhedral crystals. Minute anhydrite crystals are individually surrounded by gypsum. No dolomite was observed, but considerable iron hydroxide is present. In several places, iron hydroxide was observed surrounding long pyramidal clear spaces filled with gypsum.

Shimer gypsum.—Megascopic examination of the lower gypsum bed of the Shimer shows it to be composed of three types of gypsum:

(1) large coarse crystals of satin-spar and selenite, (2) very fine-grained white gypsum that occurs in nodules in the gypsum matrix, and (3) gypsum of intermediate grain that is massive and white. The rock has been badly weathered, being quite soft and friable, and very fine sugary-grained dolomite occurs along the fracture surfaces and in many solution cavities. The color varies from white to pale olive-gray. Some banding, due to slight differences in color, parallels the bedding.

Microscopic examination of the lower gypsum bed discloses the three sizes of the gypsum, some of the larger selenite crystals being 1–2.5 millimeters in diameter. Some cavity space occurs between the gypsum crystals. The long axis of the satin-spar crystals is usually perpendicular to the bedding. Some irregular-shaped, elongate gypsum crystals have a sort of radial structure around a common center. Small cubes of anhydrite are present in many of the gypsum crystals, but they have no apparent structural relationship among themselves or with the gypsum crystals in which they are found. Several may be in the same crystal, but each is separated from the other by gypsum. Extremely fine-grained dolomite is present, occurring in both round and wedge-shaped crystals, some of which are collected into larger aggregates. In a few places, these extremely small dolomite grains or crystals are arranged in aggregates resembling the shape and size of oölites, ranging from 0.25 to 1 millimeter in diameter. However, each of these fine crystals is surrounded by gypsum, no two being in contact.

Megascopically, the middle part of the Shimer gypsum is hard, compact, and finely crystalline anhydrite, varying between white and pallid mouse gray in color. The anhydrite has very few solution cavities, and no bedding is apparent in any of the samples, but is easily discernible in the field. A few of the anhydrite samples show definite ball-shaped radial aggregates of crystals, varying from 3 to 5 millimeters in diameter.

Microscopic examination of the middle part of the Shimer gypsum shows anhydrite and crystalline gypsum to be present, as well as streaks and stringers of iron hydroxide, and a few anhedral crystal aggregates of dolomite. The dominant mineral is anhydrite, which occurs in definite elongate crystals arranged in radial aggregates (Fig. 5). One type of cleavage cuts across the elongate anhydrite crystal; the other runs lengthwise. Thin sheets of gypsum separate most of the anhydrite crystals and are also found along the cleavage planes. Definite solution channels, now filled with gypsum, extend to the center of the radial masses of anhydrite, where more gypsum is present.

Many of the present surfaces of the anhydrite crystals are extremely irregular and jagged, the indentations being filled with clear gypsum. An anhydrite crystal, where separated into smaller units by gypsum along cleavage planes, still maintains the same orientation and the same optical continuity; that is, the birefringence, extinction, cleavage, et cetera, are the same for each unit. Gypsum occurs between the

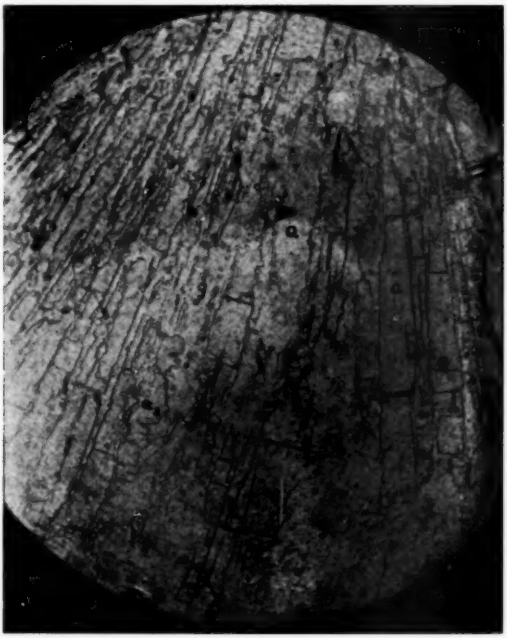

FIG. 5.—Photomicrograph of anhydrite of Shimer gypsum. *a:* anhydrite. *g:* gypsum. a_1: anhydrite crystal with irregular surface. Note vertical cleavage plane with no offsets. a_2: anhydrite crystal with irregular surface. Note jagged edge. × 85.

crystal surfaces of radiating aggregates, but the same uniformity of radiation occurs as in those radial aggregates not separated by gypsum. In small areas the gypsum is predominant, occurring in large selenitic and anhedral crystals, 0.1–1 millimeter in diameter, with small included cubes of anhydrite.

Dolomite, in small anhedral crystal aggregates with good cleavage, occurs sparingly throughout the gypsum along the cleavage planes and between the crystal surfaces of anhydrite. These dolomite aggre-

gates and individual crystals are found also in the gypsum along the fracture surfaces and solution channels through the anhydrite.

A thin-section study was made across the lower contact between the gypsum and the anhydrite. Megascopically, the contact is fairly distinct and sharply drawn, but when studied under the microscope, no definite line can be seen marking the contact, the gypsum changing to anhydrite in a distance of about 5 millimeters. The change, however, is not exactly gradual but patchy, small transverse elongate areas of anhydrite being completely isolated in the gypsum, and arranged approximately parallel with the bedding. Some open cavities were noticed in the gypsum.

As the contact is approached from the gypsum side, minute irregular bits of anhydrite are noticed within the finely fibrous anhedral gypsum crystals. Some of this massive gypsum has a radial structure, with irregular crystal edges, and occurs in the same thin sections with the radial anhydrite aggregates. Isolated patches of anhydrite with good cleavage and crystal structure occur next. Gypsum surrounds them and extends between crystals and along major cleavage planes, thus forming small cubes and rectangles of anhydrite. There is no distortion of the original radial arrangement of the anhydrite crystals. The surfaces of some of the anhydrite crystals are irregular and jagged with indentations of gypsum. Farther up the section, anhydrite becomes the dominant mineral with gypsum between the crystals and along cleavage planes. There are no solution cavities in the more solid anhydrite. Small grains of anhedral dolomite are scattered sparingly in the gypsum between the anhydrite crystals.

Megascopically, the upper part of the Shimer gypsum, that is, the gypsum above the anhydrite, is fine-grained even-textured crystalline gypsum, white in color and quite soft. It is badly weathered and full of many solution cavities, with no bedding apparent. Small areas seem to be more solid, compact, and free from cavities than others.

Microscopically, the upper gypsum bed was found to be composed of small compact anhedral crystals of beautiful fibrous selenite, with a few small irregular anhydrite fragments scattered here and there. Many solution cavities ranging from 0.1 to 1 millimeter in diameter were observed. They were oblong or oval and had their longer axes oriented nearly perpendicular to the bedding.

Lovedale gypsum.—Megascopic examination shows the rock of the Lovedale gypsum to be fine-grained, massive, and crystalline, varying from pale olive-gray to white in color. The gypsum has been badly weathered, making it fairly soft with numerous solution cavities. Con-

siderable fine-grained sugary-textured, incoherent dolomite occupies the cavities and fractures in the gypsum. Where it surrounds gypsum masses by filling the cracks and crevices, it gives the rock a nodular effect. In places, the dolomite, in beds 0.25 inch thick, appears to alternate with the gypsum in beds 1.5 inch thick. This is the only evidence of bedding.

Microscopic examination shows the gypsum to be full of solution cavities that are irregular and larger than 1 millimeter in diameter. The gypsum is composed essentially of small (ranging from very fine to 0.2 millimeter in thickness), compact anhedral crystals of fibrous selenite. Scattered clusters of fine dolomite grains in no apparent definite arrangements are found throughout the gypsum bed. Only a few irregular crystal fragments of anhydrite were observed in the gypsum matrix. The long direction of the larger gypsum crystals (where any structure can be observed) seems to be perpendicular to the bedding.

Geological Interpretations and Conclusions

The writer is convinced that the gypsum of the Blaine formation at Salt Creek Canyon has resulted from the hydration of anhydrite by circulating waters. The evidence as presented completely supports such a statement. It is summarized for clearness. The microscopic examinations show that: (1) the anhydrite crystals and cleavage fragments are completely surrounded by gypsum in nearly every case, even in the center of the anhydrite bed; (2) this gypsum also penetrates along the cleavage planes of the anhydrite crystals; (3) where the gypsum surrounds the anhydrite crystals, the present crystal surfaces of the anhydrite are jagged and irregular, with indentations of gypsum, the irregularities evidently being caused by more rapid alteration to gypsum along the cleavage planes perpendicular to the crystal faces; (4) solution channels through the anhydrite, where water penetrated to the center of the radial aggregates, causing hydration there first, and later penetrating between the crystals and along the cleavage planes of the individual crystals, are easily and readily observed; (5) there is optical continuity between anhydrite crystal fragments which have gypsum between them, that is, the cleavage occurs in the same plane, and in the same direction in both fragments, the birefringence is the same, the extinction is the same, et cetera; (6) within the same slide, along the gypsum-anhydrite contact, gypsum was found in an arrangement much like the radial aggregates of anhydrite, but irregular and without definite outline (gypsum occurring this way is suggestive of being pseudomorphous after an-

hydrite); and (7) the small irregular cubes and fragments of anhydrite found within gypsum crystals with good cleavage have no definite orientation relative to the orientation of the gypsum. If the anhydrite had formed from the gypsum it would seem reasonable to expect it to be found first along the cleavage planes and fracture surfaces where the water of hydration could easily escape. At least, some sort of definite orientation could be expected. The field evidence shows that: (1) bedded anhydrite is present in the middle of the gypsum bed; (2) the anhydrite is completely replaced by gypsum in places; and (3) the gypsum-anhydrite contact cuts across the bedding planes of the anhydrite. Most of this evidence was obtained from the Shimer gypsum, but the fact that anhydrite has been found microscopically in the other gypsums, occurring under the same conditions, and the fact that the Medicine Lodge, Shimer, and Lovedale gypsums are closely associated, leaves little room for doubt that all three gypsum beds are the result of hydration of anhydrite. In the face of such evidence, there is only one conclusion which the writer can accept, namely that the Medicine Lodge, Shimer, and Lovedale gypsums of the Blaine formation at Salt Creek Canyon have been formed by the hydration of beds of anhydrite.

No volume change is produced in the alteration of the anhydrite to gypsum in the Salt Creek area. In the first place, it is logical to assume that, if there is a volume change, some distortion of the anhydrite and gypsum beds and the overlying sediments would take place. The gypsum ledges should be thicker also in those places where the anhydrite has been completely altered. The microscopic evidence shows that: (1) there is no distortion of the anhydrite crystals undergoing alteration; (2) the radial structure of the anhydrite crystal aggregates is completely preserved until completely hydrated; and (3) the orientation of the crystals of anhydrite has not been changed by any alteration. Field evidence shows that: (1) the Shimer gypsum ledge has exactly the same thickness, whether the anhydrite has been only partially or completely altered to gypsum; (2) the anhydrite bed has not been distorted where tongues of gypsum extend out into it; and (3) no evidence of any distortion, movement, or displacement of any kind suggestive of volume change was observed in the field. The only conclusion which can reasonably be drawn by the writer is that the hydration of the anhydrite found in the Blaine gypsums in Salt Creek Canyon has resulted without volume change. Such a conclusion strikes definitely at the old point of controversy, that is, whether replacement is molecule by molecule, or volume by volume. The replacement in the area under discussion evidently was strictly volume

by volume. The gypsum molecules in excess of those required to fill the space occupied by the anhydrite were carried away by the water solutions and probably deposited as secondary gypsum in the shales below. This would account for the gypsum found in the shales below the gypsum beds.

The writer believes anhydrite to be the primary form of the calcium sulphate precipitation in the Salt Creek area. Briefly, the evidence for such a conclusion is that: (1) the gypsum of the Blaine formation has replaced anhydrite, thus indicating that anhydrite is the original precipitate; (2) the arid and salty conditions of the Permian of this area, much like the Stassfurt deposits (9, 14, 20), indicate that the calcium sulphate formed as anhydrite in an evaporating basin; (3) cores and deep drilling have encountered anhydrite primarily at the lower depths instead of gypsum; and (4) there is no proof in this area that pressure of overlying sediments has been able to dehydrate gypsum, as claimed by many.

If anhydrite was the original precipitate in this area, as believed, then on the basis of work done by Van't Hoff and Weigert (9, 21), wherein they found that anhydrite was precipitated in sea waters above 25°C. (77°F.) and gypsum below 25°C., the temperature must have been high during precipitation. Naturally, the temperature of the atmosphere must have been fairly high during the summer seasons to have maintained water temperatures above 77°F. in the evaporating basins, over a period of time long enough to precipitate and accumulate thick beds of anhydrite.

Summary of Conclusions

On the strength of the evidence obtained in the field, in the laboratory examinations of samples, and from the literature, the following conclusions have been made in regard to the gypsum and anhydrite beds of the Blaine formation at Salt Creek Canyon, Blaine County, Oklahoma: (1) the gypsum results from the hydration of anhydrite; (2) the hydration occurs without volume change; (3) the anhydrite is the primary precipitate mineral; and (4) the original precipitation of anhydrite implies a hot and arid climate.

DISCUSSION

H. L. Griley, Tulsa, Oklahoma (written discussion received, February 24, 1934): Mr. Muir has made a valuable contribution to our information about the character and origin of the gypsums of the Blaine formation.

No evidence was found which indicated a change in volume of the rock as it was altered from anhydrite to gypsum. Field observations in a wider area would have revealed certain things which seem to indicate expansion.

Pressure ridges (miniature anticlines) are particularly well developed in the Blaine gypsums of Major County, Oklahoma. Some of these folds have a width of 15–20 feet, and a height of 5–8 feet. Folding can be seen both in ledges of gypsum having the usual basal dolomite, and in the dolomite where there is a local absence of gypsum. These folds in places terminate near the middle of their apparent length at valley walls. In a few places it was seen that the subjacent shale was not involved in the movement, a small cave-like space being left beneath the fold. Lengthening of the gypsum beds also produced a type of small fold which is a combination of folding and thrust faulting.

Large "blisters" form on the upper surfaces of gypsum ledges. These affect a layer of rock gypsum 2–6 inches in thickness, and have a height of 0.5–2 feet. They appear to be forming at the present time, since weathering processes would not permit them to attain any great age. These "blisters" develop in beds which seem to be rock gypsum, but it might be shown by microscopic examination of samples that the process of alteration from anhydrite to gypsum is not yet complete.

Men engaged in structural mapping in western Oklahoma have wondered if dolomite is ever altered to gypsum, or gypsum to dolomite. Observations made by the writer do not indicate that any appreciable amount of rock has been involved in such a change. It can be seen, however, that, to some extent, rock gypsum (or the primary anhydrite) and dolomite were formed at the same time and from the same sea water.

A suggestion is made that Mr. Muir visit the properties of the United States Gypsum Company at Southard, Oklahoma, to secure samples from underground workings.

Another source of information is examination of well cuttings, and samples obtained in core-drilling. It is hoped that those in possession of such information concerning the character of the Permian formations in their unweathered state beneath the surface will publish brief notes in the *Bulletin*.

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ORIGIN OF BARTLESVILLE SHOESTRING SANDS, GREENWOOD AND BUTLER COUNTIES, KANSAS[1]

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Washington, D. C.

ABSTRACT

The Bartlesville sand, which produces high-grade oil throughout a region 100 miles long and 50 miles wide, centering in Greenwood and Butler counties, Kansas, occurs in narrow, elongate lenses, each ranging from 50 to more than 100 feet thick, 0.5 to 1.5 miles wide, and 2 to 6 miles long. The lens-shaped bodies are systematically arranged approximately end to end, forming several systems, or trends, each 25 to 45 or more miles long.

Although some facts disclosed by the study appear to indicate somewhat conflicting conclusions, much evidence clearly indicates that the sands were deposited as two systems of offshore bars of slightly different age, bordering the western coast of a shallow sea which occupied much of eastern Kansas and northeastern Oklahoma in Cherokee (Pennsylvanian) time. Certain features in the trends of modern offshore bar systems, found to be characteristic of the Bartlesville trends, are important in extending oil production into unproved areas.

A map showing the thickness of the Cherokee shale in eastern Kansas is included to show the relationship of the ancient shore lines with the Nemaha granite ridge on the west and a broad land area which extended eastward through central-eastern Kansas and there formed a low barrier in parts of Cherokee time. The probable method of burial and preservation of the ancient offshore bars is described, and examples of burial of bars in recent time are cited.

Lenses of oil-bearing sand ranging from 50 to 125 feet thick, 0.5 to 1.5 miles wide and 2 to 6 miles long, known as shoestring sands, occur in the lower part of the Cherokee shale of the Pennsylvanian series in Greenwood, Butler, and adjacent counties in southeastern Kansas. The individual lenses are arranged approximately end to end in systems called trends, each ranging from 25 to 45 miles long; two systems, known locally as the main trends, have approximately parallel courses, about 6 miles apart, northeast and southwest; two others, known as the cross-trends, extend northwest and southeast; a fifth trend, somewhat removed from the others, has a north and south course. The trends were referred to for years as the Golden Lanes. They are designated herein (Fig. 2) the Teeter, Sallyards, Lamont, Quincy, and Haverhill trends.

[1] Manuscript received, March 12, 1934. Read before the Association at the Dallas meeting, March 24, 1934. Published by permission of the director, United States Geological Survey. The paper presents results obtained from a coöperative project with the Kansas Geological Survey.

[2] United States Geological Survey.

The shoestring-sand oil fields were developed largely between 1920 and 1926, during a period of high crude-oil prices, and the oil commonly demanded a premium above the posted prices. The gravity of the oil is approximately 40° A.P.I. The principal fields will ultimately produce 7,000 to 10,000 barrels of oil per acre, and will probably average between 7,000 and 8,000 barrels. Drilling costs are low; well

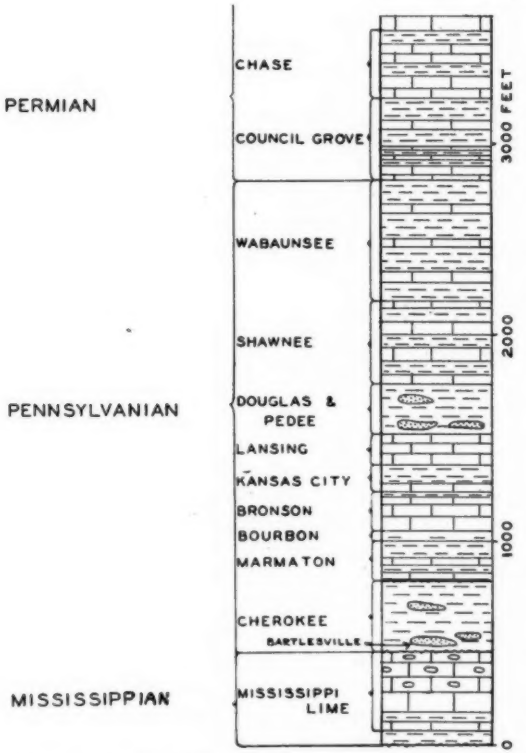

FIG. 1.—Columnar section of rocks in Greenwood-Butler counties region.

depths range between 1,500 and 2,800 feet; most of the oil is pumped with central power plants so that lifting costs are moderately small. Practically no water is produced in many of the fields; others, such as the Browning (Secs. 17–20, 29–31, T. 22 S., R, 10 E.) and Lamont (Secs. 23–26, T. 22 S., R. 12 E., and Secs. 19, 29, 30, 32, T. 22 S., R. 13 E.) fields (Fig. 2), produce considerable water. The region has been

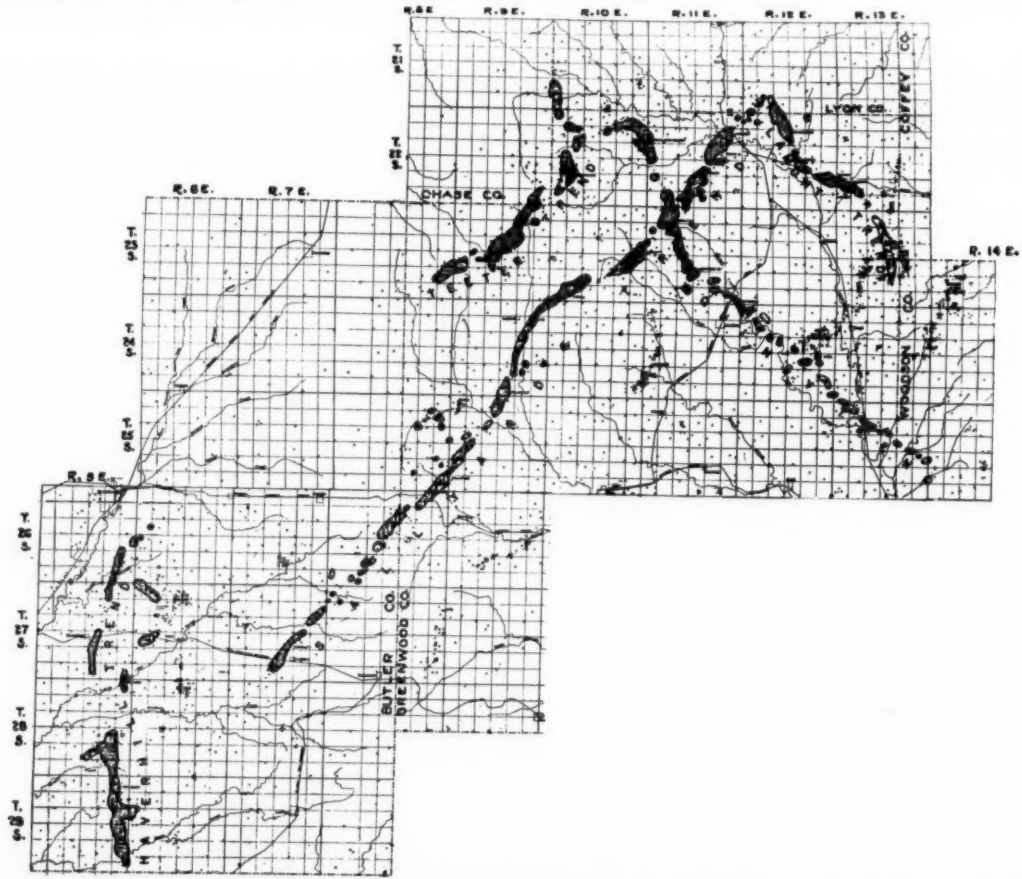

FIG. 2.—Map of Greenwood-Butler counties, Kansas, region, showing wells and shoestring trends.

an important district in Kansas for the past 15 years and reached its maximum activity in the period from 1921 to 1923. Many important pools have been discovered in more recent years, and the district yet receives considerable drilling activity. Several important extensions to fields in the Quincy trend have been made only in the past year.

The shoestring-sand deposits are called Bartlesville, although it has long been known through work by McCoy,[3] Berger,[4] and others that they are younger and stratigraphically higher than the Bartlesville sand of the type locality, at Bartlesville, Oklahoma. Weirich[5] has recently correlated the Kansas shoestring sands with the Red Fork and Burbank sands of northern Oklahoma.

The writer agrees with McCoy[6] that the evidence available indicates that the Cherokee sea, along the shores of which the true Bartlesville sand accumulated, haltingly advanced northwestward across eastern Kansas from eastern Oklahoma. It halted repeatedly long enough to allow the deposition of sand lenses bordering its shores, which were buried later by sediment as the sea expanded northwestward. McCoy has shown that a system of sand deposits in the lower part of the Cherokee shale in the vicinity of Bartlesville, Oklahoma, and extending northeastward into Kansas and southwestward toward central Oklahoma, represents a near-shore deposit of an early stand of the western shore of the Cherokee sea. Similar sandstone lenses located farther west and northwest in Oklahoma and Kansas probably represent near-shore deposits of later stages of the advancing Cherokee sea. It appears reasonable to conclude that by the time the shoestring sands of Greenwood and Butler counties were deposited, the sandstone lenses in the vicinity of Bartlesville, Oklahoma, were long since buried beneath the sediments on the bottom of the then widespread Cherokee sea.

The belief that the Bartlesville sand bodies are reflected in the attitude of the surface beds that directly overlie them is still held by a few geologists. However, detailed structural maps of the surface rocks made by the writer for three of the shoestring-sand fields, using contour intervals of 2 and 5 feet, failed to show a relationship between the

[3] Alex. W. McCoy, oral communication.
———, "A Short Sketch of the Paleogeography and Historical Geology of the Mid-Continent Oil District and Its Importance to Petroleum Geology," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 5 (September–October, 1921), p. 561.

[4] F. C. Greene, "A Contribution to the Geology of Eastern Osage County," discussion by W. R. Berger, *ibid.*, Vol. 2 (1918), p. 123.

[5] T. E. Weirich, "The Burbank Sand of Kansas and Oklahoma," *Oil Weekly*, Vol. 66, No. 10 (August 22, 1932), pp. 25–28.

[6] Alex W. McCoy, *op. cit.*, pp. 558–61. Also, oral communication.

occurrence of the buried sand lenses and the structural attitude of the surface beds. Furthermore, a compiled map showing the structure of the surface beds in much of Greenwood and Butler counties shows that the attitude of the surface beds is independent of the occurrence of the buried sand bodies.

The chief problem that the writer has had to consider is the origin of the Bartlesville sand lenses of Greenwood and Butler counties. It has been attacked mainly from the following angles: the composition and physical character of the sand material; the shapes in cross section of the sand bodies; the areal distribution of the sand lenses; their arrangement as a whole and the arrangement of individual lenses with respect to adjacent lenses; the character of the sediments enclosing the sands; and the correlation of the several local sandstone systems (trends). The detailed studies were confined to the northern part of Greenwood County, to the oil fields in Ts. 22 and 23 S. (Fig. 2) excluding the Shambaugh field (Secs. 4, 9, 10, 15, 16, 22, 27, T. 23 S., R. 13 E.). Reconnaissance studies were made of other fields.

Hundreds of oil wells and dry holes drilled in the Greenwood and Butler counties region have proved beyond a doubt that the Bartlesville sand actually occurs in elongate lenses and is for the most part absent in the areas adjacent to the lens-shaped bodies. Only a very few wells outside the trends encountered Bartlesville sand with appreciable thickness, although several wells in the south half of Lyon County, adjacent to Greenwood County on the north, may be cited as exceptions. It is an apparent fact, therefore, that the Bartlesville sand is not present as a sheet sand throughout the Greenwood-Butler counties region, or any appreciable part of the region. Accordingly, deposits of widespread distribution, such as those formed by waves in a shallow sea; near-shore sediments that progressively overlap old land surfaces or sea bottoms and thus form sheet-like deposits; coalescing deltas, or alluvial fans, wind-deposited sand or other widespread deposits produced by other depositional processes, can be eliminated as the type represented by the Bartlesville sand. A deposit of sand, distributed like that of the Bartlesville sand in the Sallyards trend (Fig. 2), which is nearly 50 miles long and less than 2 miles wide at any locality along its course, could not have been formed by any of the afore-described processes. The possibility of the sand bodies being erosional remnants of original sheet deposits is eliminated also by the areal pattern formed by the sand trends, particularly the sharp angles formed at the junction of the Sallyards and Quincy trends in Ts. 22 and 23 S., R. 11 E.

By elimination, therefore, the problem of the origin of these shoe-

string sands narrows down to relatively few possibilities. The sand deposits necessarily represent some type of very narrow, elongate bodies; only filled stream valleys and some type of shore feature, such as offshore bars or other types of bars, appear to fill this requirement. It is true that some glacial deposits, such as kames or moraines, somewhat resemble in general shape and distribution that of offshore bars or stream channel deposits, but can be distinguished from them by the type of material of which they are composed and by evidences of glacial sediments in adjacent strata;[7] no evidence of glacial deposits is recorded in wells drilled through this part of the stratigraphic section anywhere in Kansas or elsewhere near by, and none is apparent where the strata crop out in the southeastern part of Kansas and the western part of Missouri, or in Oklahoma.

COMPOSITION AND PHYSICAL CHARACTER OF SAND

The shoestring sands are composed largely of quartz, with minor amounts of feldspar, mica, and other less common minerals. Siderite (iron carbonate) forms the chief cement. The mica in the main sand bodies comprises probably less than 1 per cent of the whole and is in very fine flakes; it is much more abundant in the sandy shale beds. There is somewhat more feldspar than mica. A few fragments of marine fossils and considerable fragmentary material that probably represents plant substance have been found in the sand.

The sand in the Teeter and Sallyards trends is predominantly of fine and very fine subangular and angular grain, as is also much of the sand in the northwestern part of the Quincy trend and that in the Lamont trend. The southeastern part of the Quincy trend, from the Patterson field (Sec. 36, T. 23 S., R. 11 E.; Sec. 1, T. 24 S., R. 11 E.; and Sec. 6, T. 24 S., R. 12 E.) southeastward for 20 miles, and the Atyeo field (Secs. 30 and 31, T. 21 S., R. 10 E., and Sec. 6, T. 22 S., R. 10 E.), contain coarse-to-very coarse sand and some gravel; most of this coarse material is well rounded to subrounded. Well rounded grains of coarse sand occur sparingly distributed through the fine sand in practically the entire region. Subrounded to subangular pebbles of chert, as large as 0.5 inch in diameter, occur in the lowermost part of some of the fine sand bodies. The sand of all fields contains much silt and clay—as much as 25 per cent or more.

Stream-laid deposits characteristically are composed of a large variety of substances; the material varies abruptly in composition and size of grain, due to the fact that a stream is subjected to extremes

[7] G. K. Gilbert gives additional comparisons in "The Topographic Features of Lake Shores," *U.S. Geol. Survey 5th Ann. Rept.* (1885), p. 121.

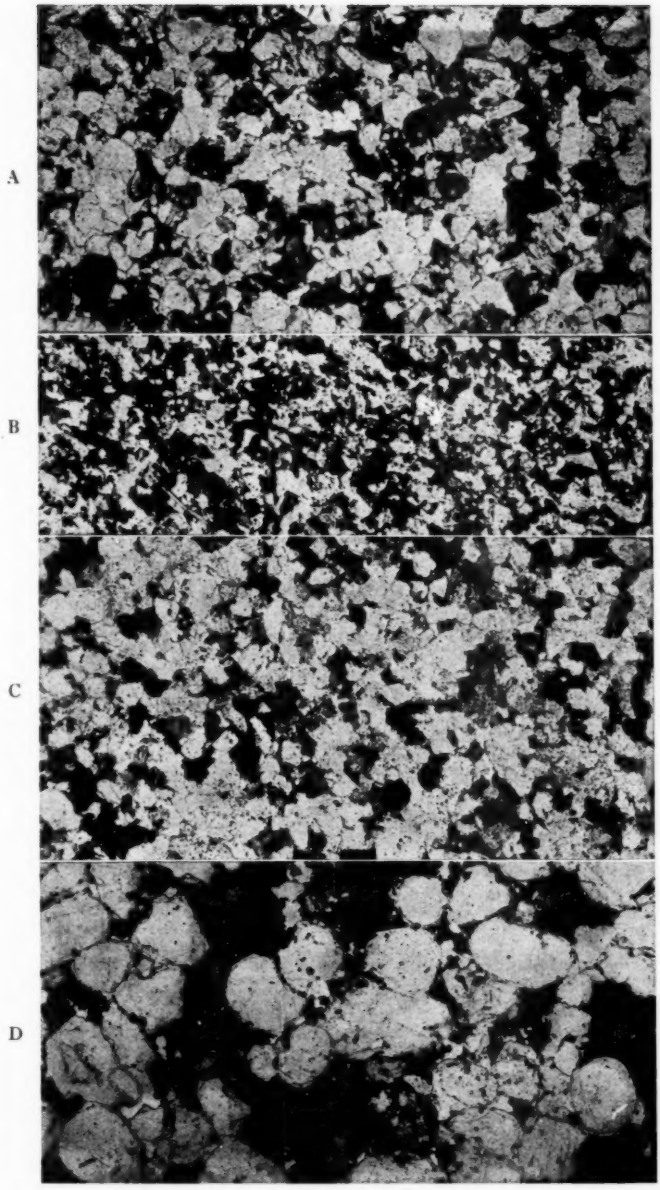

FIG. 3.—Microphotographs of thin sections of Bartlesville sand and Moberly, Missouri, channel sandstone. *A*. Specimen from Miami, Missouri, quarry in Moberly channel sandstone. *B* and *C*. Specimens from cores of Bartlesville sand in Madison oil field (Sec. 14, T. 22 S., R. 11 E.). *D*. Specimen from core of Bartlesville sand in Quincy oil field (Sec. 15, T. 25 S., R. 13 E.). Magnified 17 diameters.

in carrying capacity seasonally and during flood periods. Pennsylvanian sandstone deposits near Warrenburg and Moberly, Missouri, which have been described by Winslow,[8] Marbut,[9] and Hinds and Greene,[10] as filled stream channels, do not differ markedly in composition from the shoestring sands. Quartz is the chief constituent of the Missouri sand, but a great variety of material, including mica, feldspar, limestone, shale, and coal, also is present.

The sand of each oil pool of the Teeter, Sallyards, and Lamont shoestring trends and the northwestern part of the Quincy trend is of finer grain, somewhat less angular, and more equidimensional than the sand of the Moberley and Warrensburg, Missouri, channel deposits. The coarse sand of the southeastern part of the Quincy trend, however, is markedly more rounded and coarser than the Missouri sand. The Missouri channel sand has crudely banded, cross-bedded layers composed of a variety of substances, but chunks and core samples of the Kansas shoestring sand show finely laminated, sharply defined layers composed of grains of different specific gravities. Such sharp segregation of material of different specific gravities is more commonly accomplished by waves and currents in large bodies of water such as seas and lakes than by stream currents, which tend to dump the sediments in more or less of an unassorted mass.

The fact that dune sand is characteristically well rounded suggests that the coarse, well rounded sand in the Quincy trend represents dune sand which was picked up by a stream, reworked and deposited in its channel. However, Udden[11] found that dunes are composed largely of grains ranging between 0.125 and 0.25 millimeter in diameter. Coarse sand is present in abundance only in thin layers on the rear slopes of dunes. The fine sand which makes up the main body of dunes is much finer than the sand of the Quincy trend. These facts appear to prove that the sand bodies of the Quincy trend do not represent dune-sand deposits.

Because the materials of offshore bars commonly are washed and shifted about by waves and currents repeatedly during the bar's construction, the corners and edges of the sand grains are worn off, the sands and gravels are sorted as to different specific gravities and

[8] Arthur Winslow, "The Higginsville Sheet," *Bull. Missouri Geol. Survey*, Vol. 9 (1896), pp. 45–54.

[9] C. F. Marbut, "Geological Description of the Calhoun Sheet," *Missouri Geol. Survey*, Vol. 12, Pt. 2 (1898), pp. 158–59.

[10] Henry Hinds and F. C. Greene, "The Stratigraphy of the Pennsylvanian Series in Missouri," *Missouri Bur. Geol. and Mines*, Vol. 13, 2d Ser. (1915), pp. 95–96.

[11] J. A. Udden, "Mechanical Composition of Clastic Sediments," *Bull. Geol. Soc. America*, Vol. 25 (1914), p. 678.

sizes, and the finest material, such as silt and clay, is largely removed and carried elsewhere. Many geologists believe that a film of water surrounding the grains of wet sand tends to hold the grains[12] apart and thus prevent wear; and that the cushioning by the water film is most effective on the fine grains. This hypothesis is commonly offered to account for the fact that fine sand on our modern beaches is not so well rounded as the coarse sand.[13] The coarse sand, which predominates in the southeastern part of the Quincy shoestring trend and in the Atyeo oil field and makes up a small portion of the other shoestring trends, is more rounded than the fine sand, which, in so far as this character is concerned, is in harmony with features observed in our modern beach sands. The Bartlesville sand contains a much higher content of silt and clay than the sand of modern beaches along the Atlantic coast.

The shoestring sand contains also much more feldspar and slightly more mica than the beach sands along the Atlantic coast. It is known that the grinding action produced by the shifting of the sand on the beaches tends to destroy the grains of feldspar and mica and other soft minerals so that only durable minerals such as quartz remain in abundance on many beaches. However, fine grains of fragile minerals can be preserved throughout a long period. Martens[14] reports that grains of feldspar that must have traveled at least 400 miles along the coast and an additional 200 miles by river occur in the beach sand near Miami, Florida. Moreover, where the sources of the sands are not far from the site of deposition, the fragile minerals may be preserved in abundance. Marine sandstones of Tertiary age in California[15] contain a high percentage of feldspar grains. Most of the feldspar and mica minerals in the shoestring sand very likely had their source in the Nemaha granite ridge area which was only 25 miles or so from the locality of deposition (Fig. 12). It does not appear unreasonable, therefore, that these minerals should not have been destroyed by transportation through so short a distance even though they may have been shifted about on the beach for a considerable time.

[12] N. S. Shaler, "Beaches and Tidal Marshes of the Atlantic Coast," *Natl. Geog. Soc. Mon.* (1896), pp. 150–51.
J. G. Goodchild, "Desert Condition in Britain," *Trans. Edinburgh Geol. Soc.*, Vol. 7 (1897), pp. 203–22.
W. H. Twenhofel, *Treatise on Sedimentation* (1926), pp. 168–69.

[13] G. R. McCarthy, "Coastal Sands of the Eastern United States," *Amer. Jour. Sci.*, 5th Ser., Vol. 22 (1931), pp. 35–50.

[14] J. H. C. Martens, "Resistance of Feldspar in Beach Sand," *Amer. Mineralogist*, Vol. 16 (1931), p. 531.

[15] R. D. Reed, *Geology of California* (Amer. Assoc. Petrol. Geol., 1933), pp. 126–27, 149–50, 243.

The conclusion must be reached that, on the basis of the composition and physical character of the sand, the evidence is somewhat conflicting, in so far as it indicates whether the shoestring-sand bodies originated as stream-channel or beach deposits.

SHAPES IN CROSS SECTION

Because stream-channel and offshore-bar deposits differ markedly in their shapes in cross section, it is believed that the shapes of cross sections of the shoestring-sand bodies indicate which of these types of deposits is represented by them.

When a stream channel is filled with sediment, it imparts to the resulting deposit a valley-shaped base, and the deposit is more widespread in the upper part than in the lower part. An offshore bar is quite different in cross section. It is built on a base, comparatively a plane, that slopes slightly basinward, and its top forms a low arch; the lower part of the deposit is more widespread than the upper part.

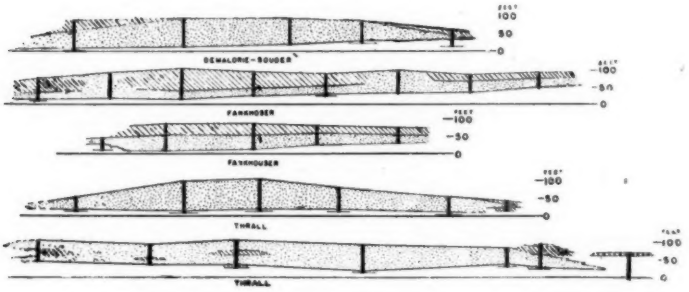

FIG. 4.—Crosss ections of Bartlesville sand bodies in the Thrall (Sec. 31 and 32, T. 23 S., R. 10 E), Fankhouser (Secs. 4 and 5, T. 22 S., R. 12 E.), and DeMalorie-Souder (Secs. 1 and 12, T. 22 S,. R. 10 E.) oil fields.

Scores of cross sections of the shoestring-sand lenses based on well records, in part supplemented by cuttings, were made across the oil fields in the area in Greenwood County that was studied in detail, and others were made for the Haverhill oil pool (Secs. 22, 27, and 34, T. 27 S., R. 5 E.) in southern Butler County and the Atyeo oil pool in Lyon County, outside the detailed area. A few of these are reproduced in Figure 4.

In most cross sections the base of the sand body approaches a plane, the sand body is widest at the base, is thickest in the middle, and its upper surface is convex upward. The cross sections show, also, the very significant fact that the bases of the sand bodies of the

Teeter and Sallyards trends when deposited had a low slope southeast and that the sand bodies of the Lamont and Quincy trends slope southwest.

Subsurface contour maps, drawn on the top of the Bartlesville sand, show the upper surface of the sand bodies of all the fields to be convex upward; a structure contour map of the entire region, drawn on top of the Bartlesville sand, which is not reproduced here, shows trends of elongate ridges along the shoestring-sand trends. This is illustrated by the map of the Scott field of the Teeter trend. It is noteworthy that the map indicates that the sand is lower on the southeast

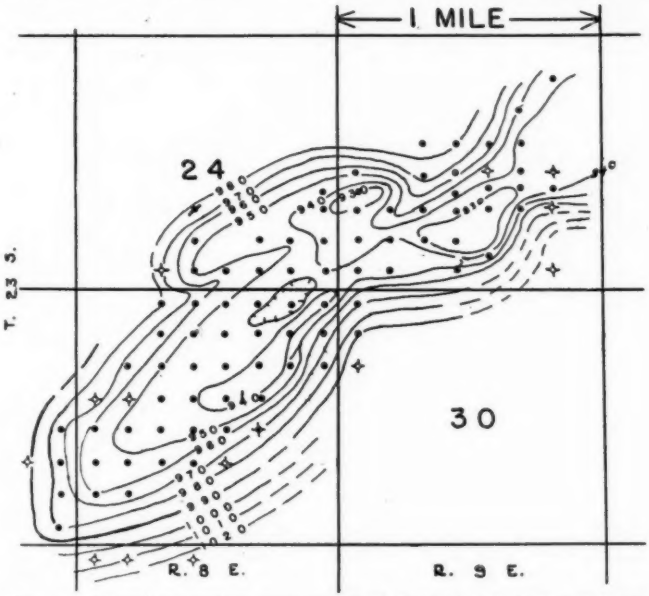

FIG. 5.—Subsurface structure contour map of Scott oil field. Contours drawn on top of Bartlesville sand. Contour interval, 10 feet. Elevations in feet below sea-level.

side of this field than on the northwest side, and if the regional dip of the strata which is toward the west is removed, the eastern margin of the sand lens is seen to be even lower than shown here. This fact is additional evidence that the surface on which the sand lens rests had an original eastward slope.

A block diagram on which the sand body is shown in perspective has been prepared for each of several of the oil fields. The diagram of the Burkett field (Fig. 6) was made directly from well records and no

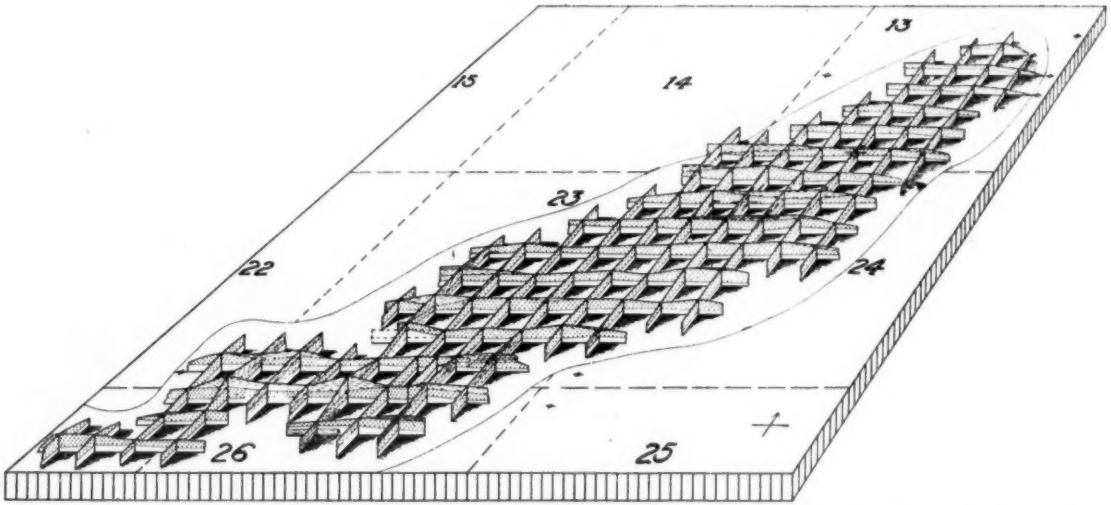

FIG. 6.—Block diagram of Bartlesville sand in Burkett oil field (T. 23 S., R. 10 E.). Vertical lines at intersections represent wells. Dotted pattern represents Bartlesville sand. Dashed pattern represents shale at Bartlesville horizon. White band below sand represents underlying shale (wells did not penetrate this lower shale so deeply as shown in most wells). Light line encircling diagram represents approximate boundary of sand body if projected as in Figures 7 and 8. Sand body is about 75 feet thick in central part of field. Wells are spaced 660 feet apart. Symbol -⊙- represents dry holes. Section lines shown by dashed lines.

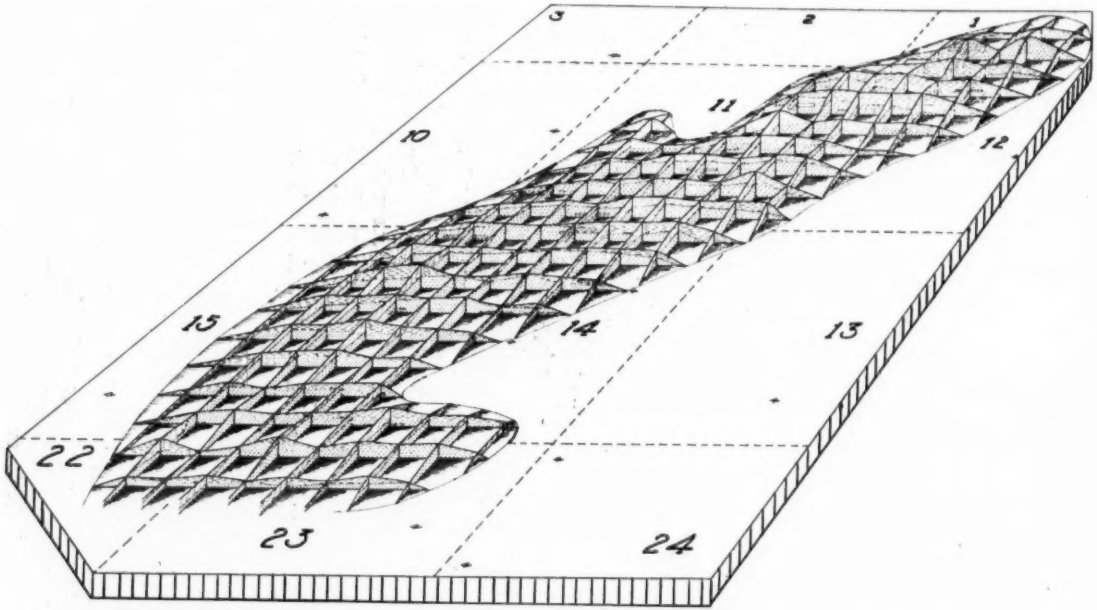

FIG. 7.—Block diagram of Bartlesville sand in Madison oil field (T. 22 S., R. 11 E.) Symbols used similar to those used in Figure 6. Cross sections have been projected to hypothetical boundary of sand body. Intersections lacking wells are shown by dashed vertical lines. Wells shown by solid vertical lines. Sand is about 75–100 feet in maximum thickness.

logs were discarded. It shows the sand to be a lens-shaped body with a convex upper surface, and a plane base sloping at a low angle southeast; the widest part of the lens is made by the lowermost part of the sand. On the diagram, the solid vertical lines at the intersections represent wells. The sand is about 75 feet thick in the central part of the field. The wells are spaced 660 feet apart.

A block diagram (Fig. 7) of the Bartlesville sand of the Madison field of the Sallyards trend shows the same features. In this diagram, however, a plane base has been assumed, after it was learned from numerous cross sections made across the field that the base of the sand is actually a plane sloping slightly eastward. Because of the assumption made, this diagram represents merely an interpretation, whereas that of the previous figure represents the facts just as recorded in the well logs. The diagram (Fig. 8) of the DeMalorie-Souder sand body of the Quincy trend is similar to that shown for the Madison field. The sand has a maximum thickness of a little more than 100 feet in this field.

The scores of cross sections drawn, the block diagrams, and the subsurface contour maps appear to establish the fact that the upper surfaces of the shoestring-sand bodies are convex upward, and that the bases are approximately planes, facts which force the conclusion that in cross section the shoestring-sand bodies appear to be similar to offshore bars rather than to filled stream channels.

The study of cross sections made through the Wick (Secs. 22, 27, 28, 33, and 34, T. 22 S., R. 11 E.), Seeley (Sec. 32, T. 22 S., R. 11 E.; and Secs. 5, 6, 7, 8, 16, and 17, T. 23 S., R. 11 E.), and Burkett (Secs. 13, 23, 24, 26, and 27, T. 23 S., R. 10 E.) sand bodies at the junction of the Sallyards and Quincy trends (Fig. 2), revealed that the base of the sand in the Seeley field of the Quincy trend is about 40 feet lower stratigraphically than that in the Wick and Burkett fields of the Sallyards trend; which seems to establish the fact that the Quincy trend is of earlier date than the Sallyards trend.

DISTRIBUTION OF SAND LENSES

The distribution of the sand lenses presents certain features that appear to be capable of fairly definite interpretation. Meandering courses are common features of stream channels, particularly of those streams that have reached an advanced age and are filling their channels rather than cutting or maintaining a grade. The channel of Mississippi River, shown on the topographic sheets of the United States Geological Survey, may be used as an illustration. It is marked by wide meanders throughout its course, except the lowermost part across its delta.

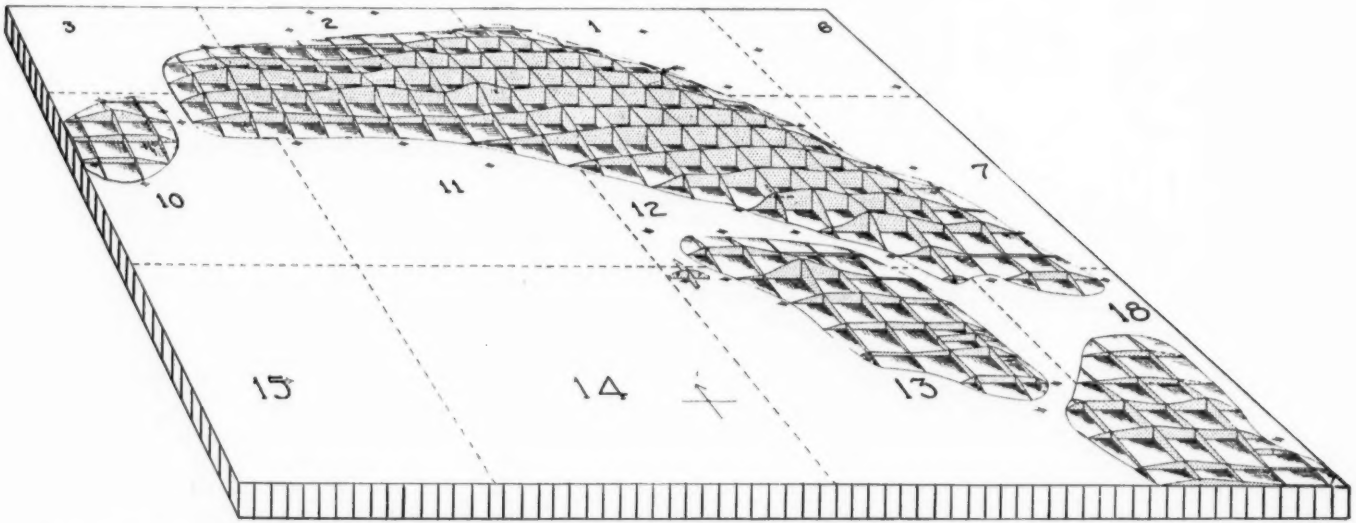

FIG. 8.—Block diagram of Bartlesville sand in DeMalorie-Souder oil field (T. 22 S., Rs. 10 and 11 E.). Symbols used are similar to those in Figure 6. Sand is about 100 feet thick in central part of field. Sandy shale that overlies sand body is not shown.

Also, the map of an oil pool in the Majkop district in Russia in which the oil-containing rocks have been interpreted[16] as stream-laid sediments filling a stream channel is reproduced in Figure 9. Maksimov's original map is contoured and shows the definite channel shape of the oil-bearing beds in cross section and the meandering areal pattern formed by the distribution of the sand deposit. The map is based on the records of several hundred wells.

If comparisons are made of the maps of Mississippi River and the filled stream channel of the Majkop oil district of Russia with maps (Fig. 2) showing the distribution of the shoestring-sand bodies in Kansas, there appears to be much that is dissimilar. The course of the Sallyards or of the Quincy trend in Kansas is too straight to fit even the course of Mississippi River across its delta. The meandering course of the channel sandstone of the Majkop oil field of Russia and the meandering Mississippi River channel above New Orleans are in distinct contrast to the course of each of the Kansas sand trends. The course of the Teeter shoestring trend and that of the Lamont trend could conceivably satisfy the requirements for a stream course, such as the lower part of Mississippi River.

But if maps of the Kansas sand trends are compared with the maps of the offshore bars that border parts of our coasts, certain parallelisms are striking. A part of the New Jersey coast which includes Atlantic City is shown on Figure 10, copied from the United States Coast and Geodetic Survey's Chart 1217. Lines, 6 miles apart, were drawn to aid the reader in making comparison of this area with the Kansas area, which is marked off in townships, 6 miles square. The elongate offshore bars of sand bordering the New Jersey coast are shown in black. The part that stands out of water is shown in solid black, and the narrow submerged slopes on the ocean side are shown by a stippled pattern. The shaded zone, that is landward from the bars, is occupied by lagoonal marshes, containing numerous thoroughfares of open water, shown in white. The breaks between the bars connecting the ocean and the lagoons are called tidal inlets.

On the right half of Figure 10 is a sketch of the Sallyards and Lamont shoestring trends. There, the solid black areas represent the shoestring-sand bodies; the white area containing dotted lines is an open sea; the shaded area represents lagoonal marshes, within which open water thoroughfares are shown in white. The sand bodies shown are definitely known from the records of the wells; many of the broad

[16] M. Maksimov, "Investigation of Interrelation of Horizons Producing Majkop Light Petroleum in Conjunction with Genesis of Majkop Arm-Like Oil-Pool," *Petrol. Industry*, Pts. 11 and 12 (1929), pp. 813-34, Pl. 3.

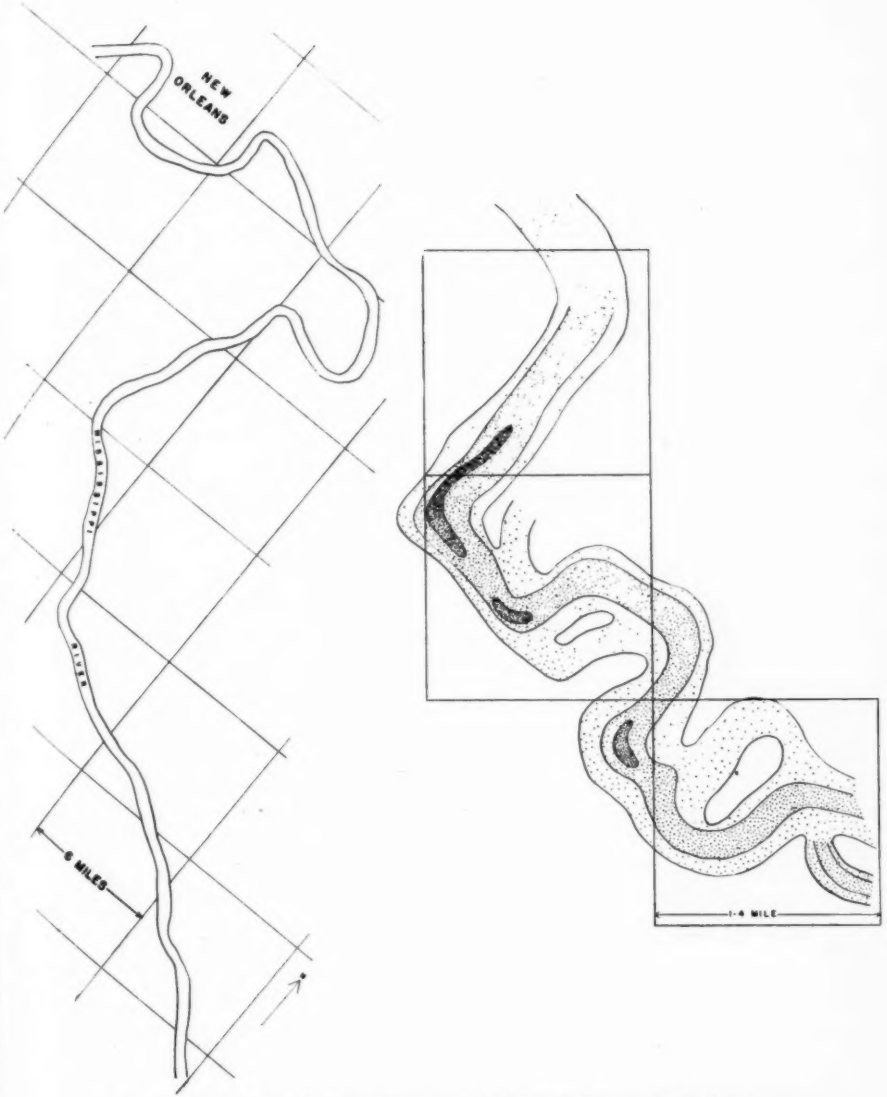

FIG. 9.—Left: sketch of Mississippi River across its delta. Right: map of a buried stream channel deposit in Majkop oil district, Russia (after Maksimov).

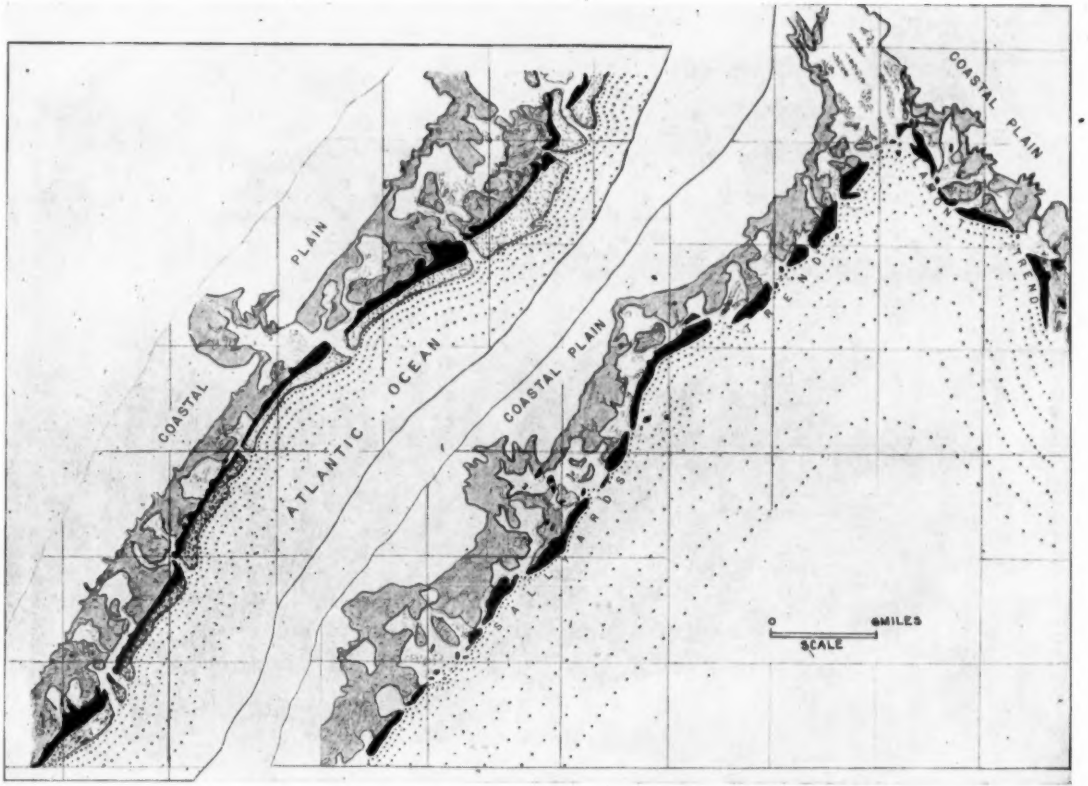

FIG. 10.—Left: Sketch of part of New Jersey coast. (After *U.S. Coast and Geodetic Survey Chart 1217*). Dotted lined area represents Atlantic Ocean; solid black with adjacent stippled areas represents offshore bars; shaded area at left of bars represents lagoons with coastal plain farther left.

Right: Sketch of part of shoestring-sand area. Dotted lines represent Cherokee sea; solid black represents Bartlesville sand bodies; shaded area represents lagoons.

areas adjacent to the sand bodies are known, also from wells, to contain no sand of any appreciable thickness and purity; the other features, such as the marshes, ocean, thoroughfares, and shore lines, are hypothetical. Nearly all the areas believed to be tidal inlets are known from the records of wells to contain no sand; they are narrow areas, between thick bodies of sand of the main oil fields.

Several features in the offshore-bar system along the Atlantic coast are duplicated in the Kansas shoestring trends. Offshore bars are built[17] largely by storm waves that roll in from the open sea, brush up sediment from the shallow nearshore bottom, and deposit it along the line of breakers a mile or more from shore. Waves most commonly strike at an angle and set up currents parallel with the shore, known as longshore currents. The longshore currents extend the offshore bars by making additions at their ends and in so doing cause the growing end of each individual bar to be offset seaward with respect to its neighbor. This offset feature is exhibited on almost all parts of the Atlantic coast, but is particularly well developed along the south shore of Long Island (Fig. 11), where there is a westward longshore current; the western ends of the bars are building westward. The tidal inlets between the bars are kept clean of sediments by the swift currents set up by the outgoing tides.

The sand bodies of the Teeter and Sallyards shoestring trends have the offset relationship of adjacent sand bodies remarkably well developed. The offsets are accentuated if lines are drawn lengthwise down the middle of each sand body and projected somewhat beyond the boundaries of the ends. In the Sallyards trend and in the Teeter trend each sand body, with the exception of that of the Wick oil field, is offset westward with respect to its neighboring sand body on the northeast. In the Lamont trend, and in part of the Quincy trend, each sand body is offset on the northeast with respect to its neighboring sand body on the southeast. The series of small sand bodies in the southeastern part of the Quincy trend fail to show any development of this feature. These offset features are not found in a deposit formed by the filling of a stream channel and as pointed out by Rich,[18] in his description of oil-bearing stream-channel sand deposits in the easternmost part of Kansas, a stream-channel deposit is a continuous body; it is not broken into segments by narrow areas devoid of sand, such as the gaps between the sand bodies in the trends of Greenwood and Butler counties.

Right: Sketch of part of shoestring-sand area. Sand bodies; shaded area represents lagoons.

[17] N. S. Shaler, "Beaches and Tidal Marshes," *Natl. Geogr. Mon.* (1896), pp. 151–52.

[18] J. L. Rich, oral communication.

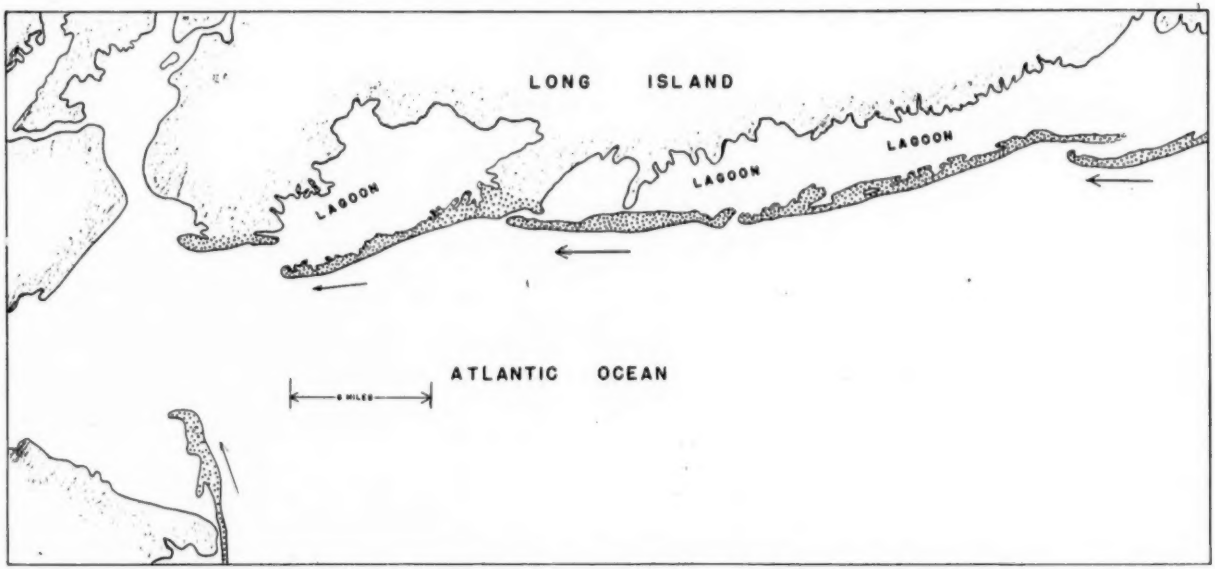

FIG. 11.—Sketch of south shore of Long Island, New York, showing offshore bars. Arrows indicate directions of longshore currents.

CONCLUSIONS

With the foregoing facts in mind, the writer's conclusions are that the shoestring-sand bodies were formed as offshore bars bordering the shores of a broad embayment on the western margin of the Cherokee sea, which occupied eastern Kansas and Oklahoma. The interbedded marine and non-marine sediments in the Cherokee shale indicate that the water body migrated repeatedly back and forth across much of eastern Kansas. A map (Fig. 12) representing the thickness of the Cherokee shale in eastern Kansas shows that the formation is thin in a broad, loosely defined area trending slightly south of east through Lyon, northeastern Greenwood, Woodson, Allen, and Bourbon counties. It appears probable that this area stood at a slightly higher elevation than adjacent areas and so received less sediment during parts of Cherokee time. It is conceivable that, during certain periods when the Cherokee waters were restricted in eastern Kansas, parts of this area actually stood above the water level, as broad expanses of mud flats. During one of the withdrawals of the sea, it is suggested that it halted for a period of time, with its western shore near the position of the Teeter shoestring trend, and extending thence southwestward toward Oklahoma, and with the northeastern shore at about the position of the Quincy trend. During the time represented by the Teeter-Quincy stage of the Cherokee sea (Fig. 13), a system of offshore bars was gradually built up near shore. It is assumed that the sea had recently receded; therefore, the shore line must have rested on a surface formerly a part of the sea floor, and so should not have had sharp irregularities in outline.[19] The simple outline formed by the Teeter and Quincy trends is in harmony with this conception.

Subsequent to the Teeter-Quincy stage the shallow areas near the margins of the sea gradually filled with sediments; the lagoons back of the offshore bars silted up; the shore lines were pushed seaward slightly, and the lagoonal marshes encroached upon the offshore bars. Inasmuch as the land bordering the sea was a coastal plain of very low relief, fresh-water swamps probably bordered the salt-water swamps, and as the salt-water lagoons migrated seaward the fresh-water swamps followed but remained on the inner borders of the swamp lands. A coal bed reported to be 5 feet thick, overlying the sand body of the Theta oil field in Secs. 8 and 17, T. 22 S., R. 10 E., in the Teeter trend, bears evidence of this sequence of events. The offshore bars of the Teeter trend, and the northwestern half of those

[19] D. W. Johnson, *Shore Processes and Shoreline Development* (1919), pp. 186–87.

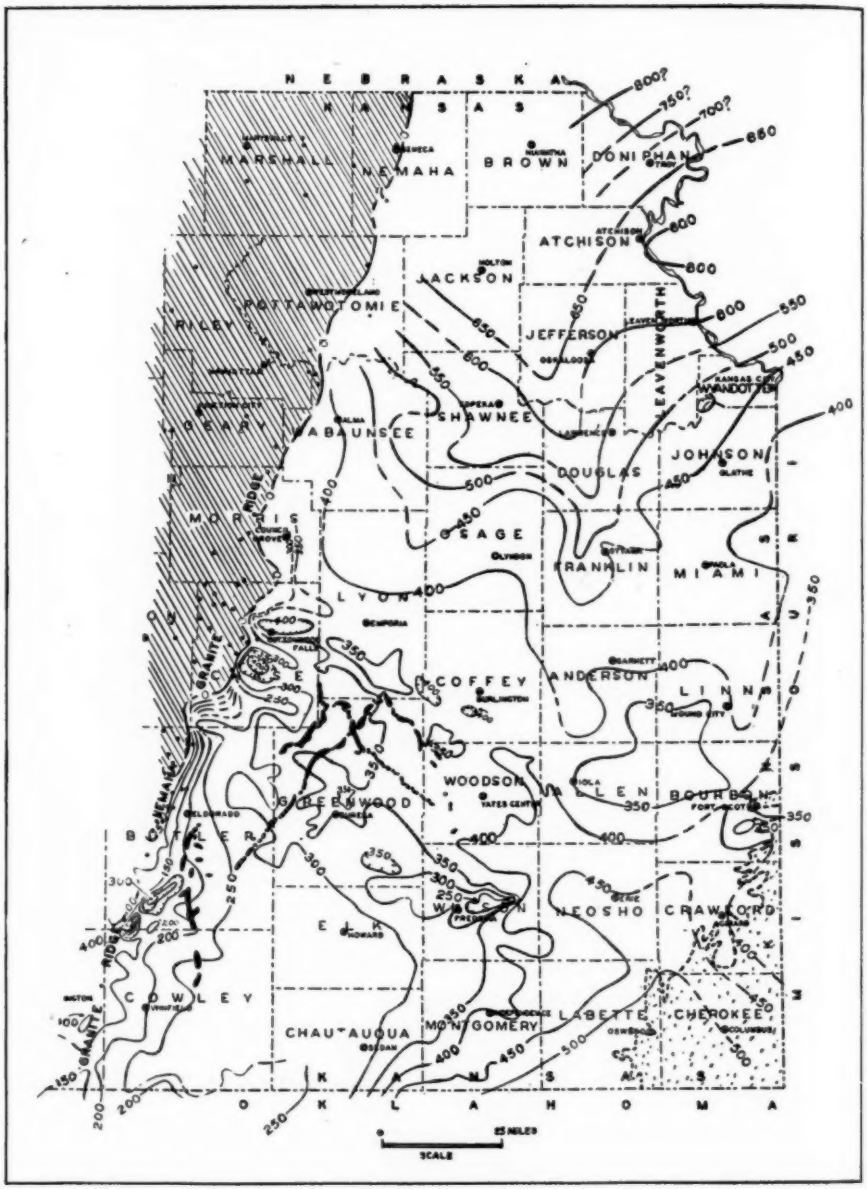

FIG. 12.—Sketch map of eastern Kansas showing thickness of Cherokee shale. Lines join points of equal thickness. Stippled area in southeastern part of map represents outcrop of Cherokee shale. Cross-lined area in western part of map contains little or no Cherokee shale. Solid black splotches represent shoestring sands discussed herein. Dots show wells that reached "granite."

of the Quincy trend, were buried, at least in part, by the encroaching marsh and lagoonal sediments.

It is suggested that following this, or during this silting-up process, the broad embayment of the Cherokee sea that occupied the Greenwood-Butler counties region shifted bodily eastward until its shore

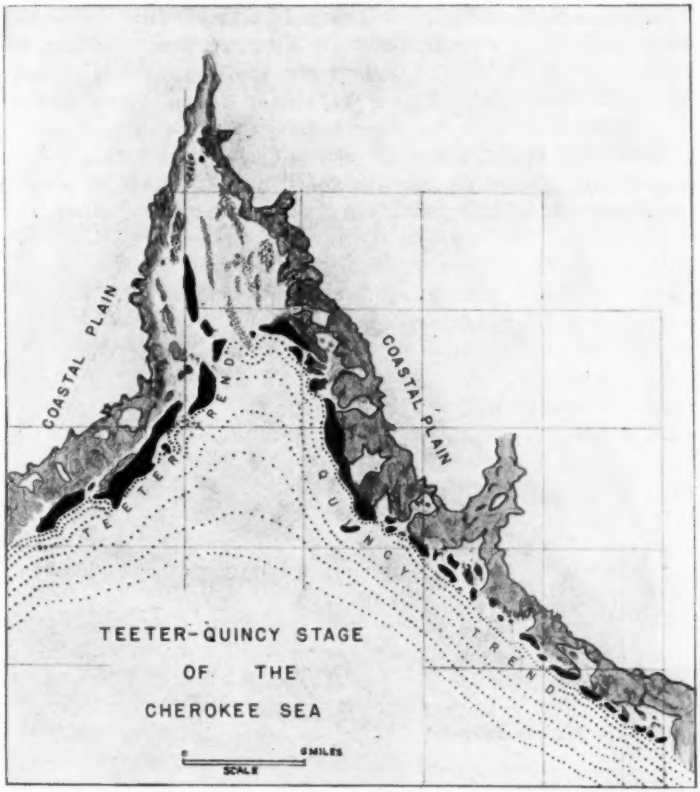

FIG. 13.—Sketch of Teeter-Quincy stage of Cherokee sea. Explanation similar to that given on Figure 10 (right half).

line stood only a few miles back from the present site of the shoestring sand bodies of the Sallyards and Lamont trends. The mechanics of this migration are of course not known, but a slight subsidence in the main trough of the Cherokee basin, which lay 50 miles farther east (Fig. 12), accompanied by a slight elevation in the region of the

Nemaha granite ridge, which lay on the west, could have accomplished it. The very thick sedimentary column in eastern Kansas indicates that, throughout a very long period, subsidence occurred along the trough of the Cherokee basin; likewise, the thinning of several parts of the entire column of Pennsylvanian sediments overlying the Nemaha granite ridge area indicates periodic or continuous uplift in that region. Students[20] of shore lines believe that fluctuations of level and changes in the position of shore lines have been very common throughout geologic time. Accordingly, the supposition that some change in level occurred during that part of Cherokee time occupied by the formation of the shoestring sands seems reasonable.

Following Shaler,[21] a simple eastward tilting of the region between the Nemaha granite ridge and the trough of the Cherokee basin would necessarily occur about a fulcrum, or area of no motion, as indicated

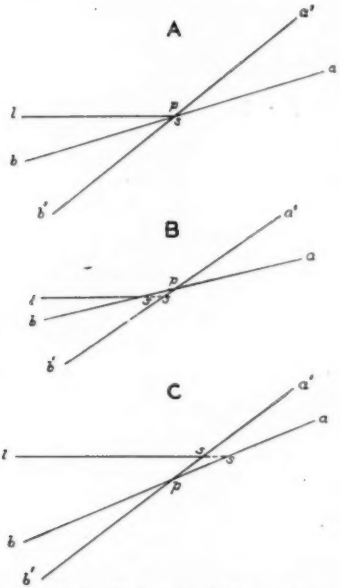

FIG. 14.—Fulcrum point (after Shaler). In *A*, *B*, and *C* lines *ab* represent land before the movement, *a'b'* after the movement; *ss*, position of shore line; *sl*, sea-level; *p*, pivotal point. *A*. Fulcrum point coincides with position of shore line. *B*. Fulcrum point is on land. *C*. Fulcrum point is seaward.

[20] N. S. Shaler, "The Geological History of Harbors," *U.S. Geol. Survey 13th Ann. Rept.*, Pt. 2 (1893), pp. 110–11.

[21] *Ibid.*, p. 112.

in Figure 14. The neutral point on a line extending from the interior of the land area to the adjacent sea basin

> may occupy either of three positions in relation to the shoreline. It may be just at the coast [Fig. 14*A*], in which case a good deal of upward and downward movement at either end of the section may take place without any alteration in the position of the shoreline, or the pivotal point may be some distance within the land [Fig. 14*B*], in which case the movement may lead to a gain of the sea upon the continent. In the third possible condition the point of no motion may be seaward of the shore [Fig. 14*C*], when, though the nature of the movement may be exactly the same as before, the coast line will rise and the land gain upon the sea.

If, subsequent to the deposition of the offshore bars of the Teeter and Quincy trends, the broad region on the west flank of the Cherokee basin was tilted eastward, the fulcrum point for the movement being east of, or basinward from the west shore, the conditions illustrated in Figure 14*C* must have held. Both shores of the Greenwood County arm of the sea shifted eastward, the western shore migrated seaward and the eastern shore encroached upon the low land that lay on the northeast. Because the land areas bordering the Cherokee sea in Kansas were coastal plains only slightly above sea-level, and because the water body was probably very shallow, an elevation or depression of only a few feet would shift the shore lines several miles. The shore lines bordering the shoestring sands were shifted only 4–10 miles, so that the relative change in elevation that took place is believed to have been very slight. Conditions here may have been similar in some respects to parts of the present Texas and Louisiana coast bordering the Gulf of Mexico, which would be inundated 15 or more miles back from the present shore line if the area were to be depressed 5 feet or less.[22]

The new western shore rested on the former sea bottom and so it should have had a simple outline;[23] the new northeastern shore, however, rested on a former land surface,[24] and so should have had an irregular outline, because a land surface is more irregular than a sea bottom. The offshore bars built along the borders of these newly formed shore lines appear to harmonize with these assumptions. The Sallyards offshore-bar system, which bordered the western shore, forms an almost straight-line course for nearly 50 miles, the chief departures being in the form of wide sweeping curves, such as that of

[22] Donald C. Barton, "Surface Geology of Coastal Southeast Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 10 (October, 1930), p. 1307, Fig. 4.

[23] D. W. Johnson, *op. cit.*, pp. 186–87.

[24] *Ibid.*, pp. 172–86, 272–345.

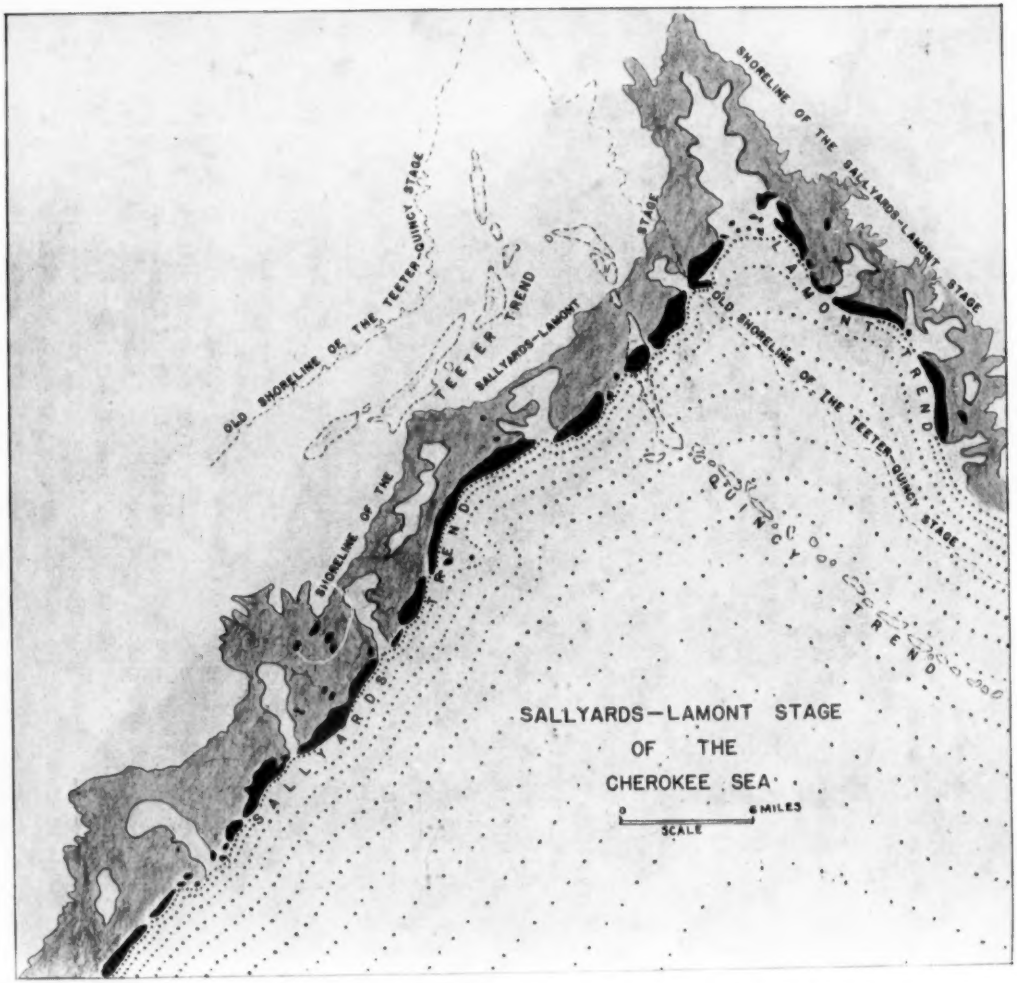

FIG. 15.—Sallyards-Lamont stage of Cherokee sea, showing also by dashed lines position of earlier Teeter-Quincy [illegible] Explanation same as in Figure

the sand body of the Agard oil field (Secs. 1, 11, 12, 14, 15, 22, 23, 26, and 27, T. 24 S., R. 9 E.). In contrast, the arrangement of the sand bodies of the Lamont trend, which bordered the northeastern shore, which lay on a former land surface, is the most irregular of any of the shoestring-sand trends in the region.

The western shore of the sea in this later stage, which the writer has called the Sallyards-Lamont stage of the Cherokee sea (Fig. 15), crossed the northeastern shore line of the earlier Teeter-Quincy stage in the vicinity of the Seeley oil field. The southeastern part of the Quincy trend must have been far out in the sea, 10–15 miles from the new northeast shore and, no doubt, the sand bodies there were below sea level. In this position the waves must have attacked these sand bodies and attempted to destroy them, because they formed irregular promontories on the sea floor. The fine material of the sand bars was readily removed under ordinary stable weather conditions, but the coarse material no doubt had a tendency to remain, except when subjected to the forces of strong storm waves and strong currents. Consequently, it does not seem improbable that parts of the old offshore bars might have escaped destruction under the new set of conditions. At any rate, it is a fact that numerous small sand bodies composed of material that is much coarser than that of most of the large bar-shaped sand bodies in the region have been found by wells in an almost straight-line course across the eastern part of Greenwood County. The assumption is that they are remnants of former large bars that were partly destroyed not long after they were built.

As pointed out by Gilbert,[25] shore features are some of the most perishable of geologic phenomena. Consequently, it would appear that some unusual combination of favorable conditions must have existed to have permitted the preservation of the shoestring-sand bodies. It has been suggested that, subsequent to the deposition of the offshore bars of the Teeter and Quincy trends, the western flank of the Cherokee basin was tilted; the tilting should have subjected the offshore bars of the Teeter trend to erosion, unless they were protected in some manner. It is a fact, however, that logs of wells drilled into the sand bodies of the Teeter trend fail to show any pronounced erosion features, and so it is probable that little or no erosion occurred there. The land that bordered the sea is thought to have been a broad coastal plain and swamp land which stood only a few feet from sea-level, where streams were able to accomplish but little erosion. Furthermore, the withdrawal of the sea was not accomplished by deformation alone but was probably brought about in part by the

[25] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey Mon.* 1 (1890), p. 101.

FIG. 15.—Sallyards-Lamont stage of Cherokee sea, showing also by dashed lines position of earlier Teeter-Quincy

silting up of the basin margins. It is believed that the change in elevation of the land was so slight and so gradual that the offshore bars of the Teeter-Quincy stage were actually buried by muds and marsh debris before the embayment of the Cherokee sea was shifted eastward to the position occupied during the later stage.

There are localities on our present coasts where old offshore bars are now part of the coastal plain and are bordered on the seaward side by marshes and recently formed offshore bars; according to Shaler,[26] examples may be seen at many places along the eastern coast of Florida. Shaler[27] described an area on the coast of Massachusetts where an ancient offshore bar lies in the midst of the lagoonal marsh that lies behind an offshore bar which recently has been built some distance seaward. Parts of the ancient bar are exposed above the swamp debris, where it forms a disconnected ridge in the midst of the swamp. Shaler's cross section showing the relationship of the old and new offshore bars is reproduced in Figure 16.

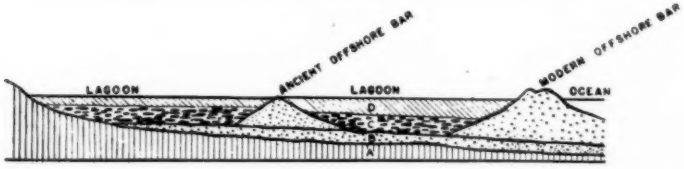

FIG. 16.—Cross section of Plum Island, Massachusetts (after Shaler). *A*. Bed rock. *B*. Conglomerate. *C*. Silt and plant debris, et cetera. *D*. Lagoon and marsh.

The few localities cited where offshore bars are being buried and preserved on our modern coasts would appear to establish the fact that under favorable conditions preservation of such shore features can be accomplished. The low, swampy coastal plain that is believed to have characterized the region bordering the Cherokee sea in Kansas probably provided conditions that were more favorable for the burial and preservation of shore features than those cited on our modern coasts.

POSSIBILITY OF DISCOVERING ADDITIONAL SHOESTRINGSAND OIL FIELDS

The oil producer is interested in the interpretation of the origin of the shoestring-sand bodies primarily to whatever extent it enables him to discover more oil fields. If studies of the facts revealed by the

[26] N. S. Shaler, "The Geological History of Harbors," *U.S. Geol. Survey 13th Ann. Rept.* (1893), p. 187.

[27] ———, "Sea-Coast Swamps of the Eastern United States," *ibid., 6th Ann. Rept.* (1885), p. 382.

development of the oil fields indicate the locations of untested areas that are prospectively valuable for oil, they are of very practical worth. Such interpretations are believed to be possible from the study of the shoestring-sand oil fields. For instance, it has been shown that buried river-channel deposits should exhibit certain characteristics that are in many ways decidedly different from those of coastal features, such as offshore bars. The correct interpretation of the origin of the known sand bodies is accordingly essential to the projection of their trends into undrilled areas, and is particularly important in interpreting the information disclosed by prospect holes that fail to locate a new sand body.

It is reported that more than 75 per cent of the present coast lines of the world are fringed with beach-sand deposits. It takes but little optimism to conclude that offshore bars were formed along the ancient shores of the Cherokee sea for many miles beyond the present known extremities of the shoestring-sand trends. However, assuming that offshore bars in addition to those now known, were formed, they may not have been preserved.

Shore features are perishable,[28] and it is only under the most favorable set of conditions that they are not destroyed. The physical conditions under which the shoestring-sand bodies were buried are perhaps more difficult to reconstruct than those that made possible the deposition of the sand. But the fact that the sand bodies throughout linear distances of 50 or more miles were preserved, proves that conditions were favorable for preservation over a fairly large area and suggests that such environment prevailed elsewhere in the region. The Sallyards trend has scarcely an interruption throughout its known length of 45 miles, except the few local barren areas between the sand bodies that are believed to represent the former sites of tidal inlets, and so should normally be expected to contain little or no sand. Lik wise, the Teeter trend is composed of relatively large, fully developed sand bodies, separated by narrow stretches marking the sites of tidal inlets. The abrupt terminus of the Sallyards trend at the southwest end of the Keighley oil field (Sec. 33, T. 27 S., R. 7 E.) and of the Teeter trend at the southwest end of the Scott oil field (Sec. 26, T. 23 S., R. 8 E.) appears not to be the natural thing to expect. It is the writer's belief that the Sallyards, Teeter, and Haverhill trends will be extended southwestward toward Oklahoma, and it may be found at some future time that they, together with some of the sand bodies in Osage County, Oklahoma, are parts of a continuous shore-line system.

[28] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey Mon.* 1 (1890), p. 101.

The possible extensions southeastward of the Quincy and Lamont trends appear to be less promising, because drilling has shown that the sand bodies in this region commonly occupy small areas, and so are more difficult to locate. However, the drilling depths are only about 1,500 feet here, and so many tests can be made at not great expense. Therefore, it appears reasonable to conclude that additional oil and gas pools in shoestring-sand bodies will be found in the eastern region, also.

The general scheme of a fluctuating inland sea in eastern Kansas which halted, at least twice, sufficiently long to permit shore structures, such as offshore bars, to be built and coal beds of considerable thickness to accumulate in low lands not far removed, suggests that these phenomena were not necessarily limited to two stages; there may have been others. The western shore of the Cherokee sea probably migrated across northern Butler County, between the eastern gentle slope of the Nemaha granite ridge and the Teeter shoestring trend. It is not impossible that at one period, or more, the shore remained fixed sufficiently long to permit the waves to throw up a series of offshore bars, which may have been buried by later sediments and preserved. Also, theoretically, one might conjecture further that at the period of formation of the shoestring sands, offshore bars probably formed all along the ancient shores on the west (also east) side of the Cherokee sea in Kansas, and that they therefore should be found swinging northward around the old land barrier, that extended eastward across Woodson and Allen counties, thence trending northwestward through Franklin and Chase counties, northward through eastern Wabaunsee County, thence northeastward through Shawnee, Jackson, and Nemaha counties, possibly into Nebraska.

ACKNOWLEDGMENTS

It is with a feeling of genuine pleasure that the writer takes this opportunity of expressing his appreciation for the wholehearted coöperation given by the many geologists and executives of the operating oil companies and geologists engaged in independent work; particularly for discussions furnished so freely by geologists acquainted with the geology of the region. Data that were costly to secure and knowledge that has been attained through years of experience were put at the writer's disposal by so many individuals and companies that space is not available to make specific acknowledgment; no doubt ideas were borrowed that are now incorporated in this report. Previously published reports on the origin of shoestring sands of Kansas

aided materially; Rich's discussions[29] of the sands in the easternmost part of the state were of particular value, as well as reports by Cadman,[30] Cheyney,[31] and Charles.[32] Criticism of the paper by Ralph W. Richards and by H. D. Miser, under whose direction, jointly with R. C. Moore, State geologist of Kansas, the project was carried on, is gratefully acknowledged.

DISCUSSION

F. G. HOLL, Wichita, Kansas (written discussion received, March 21, 1934): Mr. Bass has made a thorough study of the sand lenses in the lower Cherokee of Butler and Greenwood counties, Kansas, and his conclusions on the formation and origin of these sand bodies are clearly stated, and generally acceptable. His evidence leaves no doubt that the sand bodies in Butler and Greenwood counties are of the bar type and not stream-channel fillings. Kansas geologists appreciate his very nice comparisons between the sand trends and the bars on the present New Jersey coast.

In order that these sand bodies can be considered in their reasonable proportion of economic significance, it should be stated that during the last 10 years they have produced 120 million barrels of oil or almost one-third of the Kansas oil during that period.

The assignment of the trends to two stages or systems is also a very laudable effort to simplify a complex condition, and I doubt if a better arrangement can now be made, but it should be shown that there is not a complete concordance or agreement of the data here. For example, the offshore bars of the Teeter-Quincy stage have an extension northward into southwestern Lyon County, a distance of about 10 miles. The facts that this sand body is of the same characteristic bar type and that it extends landward make it difficult to fit into the pattern.

Water analyses are not in agreement with the 2-stage classification. For example, the northwestern shore bars of Bass' Teeter-Quincy stage contain water which is chemically similar to the northwestern bars of his Sallyards-Lamont stage, but this water is chemically dissimilar to the northeastern shore bars of both these stages and waters in the northeastern shore bars are dissimilar to each other.

The data furnished by these water analyses alone suggest that the sand bars of the lower Cherokee of Butler and Greenwood counties represent the accumulation of not two but four or five stages, and that with the exception

[29] John L. Rich, "Shoestring Sands of Eastern Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 2 (March-April, 1923), pp. 103–13.
———, "Further Observations on Shoestring Oil Pools of Eastern Kansas," *ibid.*, Vol. 10, No. 6 (June, 1926), pp. 568–80.

[30] W. K. Cadman, "The Golden Lanes of Greenwood County, Kansas," *ibid.*, Vol. 11, No. 11 (November, 1927), pp. 1151–72.

[31] A. E. Cheyney, "Madison Shoestring Pool, Greenwood County, Kansas," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 150–59.

[32] H. H. Charles, "Oil and Gas Resources of Kansas, Anderson County," *Kansas Geol. Survey Bull. 6*, Pt. 7 (1927).

of the Sallyards-Seeley-Madison trend and the Haverhill trend, the portions now existing are only fragmentary remnants.

N. W. BASS: Mr. Holl is one of the few Kansas geologists who has made continuous study of the shoestring-sand problem in the Greenwood-Butler counties region as it developed during the past 15 or more years. His criticism of the manner in which the Atyeo sand body (T. 21 S., R. 10 E. Lyon county) may fit into the scheme as presented is admittedly justified. The trend of the Atyeo sand body is not aligned with either the Teeter or Quincy trend, and yet is pictured in Figure 13 as being a part of the sand bodies deposited during the Teeter-Quincy stage of the Cherokee sea. This sand body is interpreted on Figure 13 as a bar within a broad bay similar to modern bars in Chesapeake and Delaware bays, shown on charts of the United States Coast and Geodetic Survey, but not reproduced here. The sand bars in Chesapeake Bay and Delaware Bay are not in alignment with the offshore bars that parallel the main Atlantic coast, but trend approximately at right angles to them. The general alignment of the Atyeo sand body with respect to the Teeter-Quincy coast line appears similar to the arrangement in the Chesapeake Bay and Delaware Bay region; consequently, it was pictured on Figure 13 as a sand bar within a bay merely to offer what appears to be a reasonable interpretation. It is admitted that concrete evidence of the former existence of a bay in the region of the Atyeo field was not found. The sand in the Atyeo field is much coarser than that in the fields near by and contains considerable limestone, chert, and sandstone believed to have been derived from Ordovician and Mississippian sediments that cropped out along the flanks of the Nemaha granite ridge.[33] These facts appear not to be out of harmony with the interpretation shown on Figure 13, because the sand of a sand bar in a protected bay would not be subjected to such severe grinding action by the storm waves as the offshore bars bordering the main shore and it might be expected to contain coarse sand that had been carried into the bay by rivers and scouring tidal currents.

The writer was unable to coördinate the new facts available concerning the character of the waters in the several fields and trends. Only a few water samples have been analyzed; too few, perhaps, to form an adequate basis for interpretation. It may be significant that the character of the water in the south half of the Madison oil field (T. 22 S., R. 11 E.) is reported to be distinctly different in character from that in the north half; wells spaced only two locations apart have the different types of waters. All data available indicate that the sand in the Madison field is a continuous body of fairly homogeneous material. In the light of this variation in the chemical character of water contained in an individual sand lens conclusions drawn from a few data on the waters in widely separated sand bodies appear unwarranted.

JOHN L. RICH, Cincinnati, Ohio: I wish to compliment Mr. Bass on a splendid piece of work, and especially on the comparison of the shoestring trends in Greenwood County with the shore features of New Jersey.

To the larger picture I can add a little. The Cherokee sea appears to have occupied the area between the Granite ridge and the Ozark uplift. The sand bars which Mr. Bass described lay along the western side of this shallow sea. One would expect that if offshore bars were built up on one side of such a sea,

[33] John S. Barwick, oral communication.

there should have been similar bars on the other (east) side. Actually we find at least two sets of bars represented on the eastern shore of the Cherokee sea. The best known and probably the best developed of these is the sand trend in which the Colony gas field was found. That trend can be traced from Colony almost continuously southward nearly to the Oklahoma line, and also northward at least as far as Garnett. Another bar, not so well known, lies east of the Colony sand bar. In east Anderson County is a very interesting situation, where a channel shoestring-sand body at least 15 miles long and containing oil or gas all the way, merges at its northwest end into a broad sand body, apparently representing the place where the channel emptied into a lagoon and the sand was strung out along the shore by the waves. A mile or so west of this is a line of sand bars containing gas—presumably contemporaneous offshore bars—such as Mr. Bass has described.

Some of the sand bodies in Greenwood County show channel characteristics. I think there were both channels and offshore bars in that area.

I doubt whether the uplift which Mr. Bass mentions as occurring in Woodson County extended entirely across the Cherokee embayment to Bourbon and Allen counties. I think it did not.

BASS: Rich's discussion here of the sand bodies in the easternmost part of Kansas is a valuable addition. The writer agrees with Rich that the broad lowland area between Lyon and Bourbon counties probably was not a continuous body of land; it probably had several waterways across it, particularly in the eastern part of the state (Fig. 12).

J. BOYD BEST, Houston, Texas: I should like to inquire as to the relationship of these sands to the Dexter and the Beaumont-Eureka anticlines. In the work which I did in the area in 1921, I mapped the Dexter anticline from the Oklahoma line through the town of Dexter and the Beaumont-Eureka anticline, which is a continuation of the folding but is situated *en échelon* on the west, from a point near the Oklahoma line through Eureka, a distance of about 60 miles. The sand bodies that had been found at that time seemed to be located a certain distance, about 4 miles, west of the folding. I thought that there was some relationship between the two, that the sand bodies were some sort of tidal current or offshore bars from some feature along the line of folding.

BASS: There is no relationship. Kansas geologists do not believe that the Dexter and Beaumont-Eureka anticlines were in existence until after Cherokee time. Cross sections across these anticlines indicate no thinning in the Cherokee shale or underlying "Mississippi lime."

BEST: What do you think of the well that penetrated red granite near the south end of the Beaumont gas field? Might that not indicate that there had been some deformation there before Cherokee time?

BASS: I do not believe so.

D. C. BARTON, Houston, Texas: Lagoonal sediments may be somewhat abnormal. I should like to ask whether any such lagoonal sediments could be recognized back of those old barrier beaches.

BASS: In the cuttings that I studied I was unable to recognize any particular type of sediment in the lagoonal side of the bars.

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PRELIMINARY STUDY OF SOURCE BEDS IN LATE MESOZOIC ROCKS ON WEST SIDE OF SACRAMENTO VALLEY, CALIFORNIA[1]

PARKER D. TRASK[2] AND HARALD E. HAMMAR[3]
Washington, D.C.

ABSTRACT

This paper presents results arising from an investigation of source beds of petroleum, sponsored both by the United States Geological Survey and the American Petroleum Institute. The paper is a preliminary report of a special investigation that has arisen in connection with the general study of source beds. An area on the west side of the Sacramento Valley in northern California underlain by a thick sequence of rocks of late Mesozoic age, that is, the Shasta series (Lower Cretaceous) and the overlying Chico formation (Upper Cretaceous), has recently been considered as prospective oil territory by several oil companies. Seeps of oil and gas are present and favorable structural features and reservoir rocks are known, but no oil in commercial quantity has yet been found. As the strata attain a thickness of 40,000 feet, the distribution of adequate source beds throughout this thick section is a very important question. The problem of the distribution of source beds was attacked by the writers by means of preliminary analyses of the organic content of 480 samples distributed fairly uniformly in the section, and by means of detailed analyses of the organic constituents of 8 samples selected as being representative of these 480 samples. Definite conclusions about the possibilities of source beds in this area are difficult to reach because of the paucity of knowledge about the diagnostic characteristics of source beds. Nearly all the results that were obtained, however, lead to an unfavorable consideration of the sediments as source beds. The organic content is low and fairly uniform throughout the entire sequence of beds. The average organic carbon content of the Shasta series is 0.87 per cent and of the Chico formation 0.6 per cent. The composition of the organic constituents of samples from the oil seeps is different from that of the sediments in the general section. This phenomenon suggests that sediments of the type that generate the oil at the seeps are not widely distributed through the general section. The uniformity in quantity and character of the organic content of the Shasta and Chico sediments leads to the inference that almost any part of this sequence of strata is as likely to be favorable for source beds as any other part. Because of the failure to find oil in the wells that have already been drilled in this area, the uniformity of the organic content is not a favorable indication of the presence of adequate source beds of petroleum in the area. This inference about the uniformity of the organic content, however, is more encouraging with respect to source beds of gas, as significant quantities of gas have been reported from the Buttes well of the Buttes Oilfields, Inc., and also from the Guinda well of the Nigger Heaven Dome Oil and Gas Company. However, despite the discouraging aspect indicated by the results of this investigation, the evidence is not very positive in character, and in no way condemns the area. It is entirely possible that adequate source beds may be present.

INTRODUCTION

During the past few years an area on the west side of the Sacramento Valley in northern California, underlain by late Mesozoic

[1] Read before the Association at the Dallas meeting, March 24, 1934. Manuscript received, May 28, 1934. Published by permission of the director of the United States Geological Survey.

[2] United States Geological Survey.

[3] American Petroleum Institute, and United States Bureau of Standards.

strata having a maximum thickness of 40,000 feet, has received considerable attention as prospective oil territory. Oil and gas seeps and the presence of gas and very minor amounts of petroleum in wells indicate that some source beds occur in this region, but a vital question is whether or not adequate source material is distributed generally throughout this tremendous thickness of strata. In an attempt to throw light on this question, tests were made by the writers to determine the distribution of organic matter, bitumen content, and volatile constituents throughout one composite section 40,000 feet thick. After these tests had been completed, the organic constituents of 8 samples—3 from the vicinity of oil seeps and 5 from the general section—were analyzed in detail in order to compare the nature of the organic matter in different types of sediments in the area. The significance of the results of this work with respect to the character of the sediments as source beds is not as fully understood as it would be if the nature of source beds were known better; but because of the present great interest in the area a preliminary report of the investigation is presented at this time.

As the paper is a preliminary report, little attempt is made to describe in detail the methods of attack or to discuss the relative merits of these methods. These features of the work will be treated more fully in a later and more comprehensive publication. Attention, however, should be called to the effect of weathering on outcrop samples. Unfortunately, the extent to which the organic content of sediments is influenced by weathering is not yet known. The writers at present are investigating the effect of weathering, but their work has not yet progressed to the state of reaching definite conclusions. Some of the data obtained from these late Mesozoic sediments seem to indicate that the organic content of outcrop samples may be less than that of corresponding well samples. Consequently, present inferences based on the organic content of outcrop samples may be subject to modification when the effect of weathering is more fully understood.

This paper represents results of a project sponsored by the United States Geological Survey and the American Petroleum Institute. Trask carried on the field work during several periods, totalling three weeks, in October, 1932, and May, June, and September, 1933. He also determined the texture of the sediments and wrote the paper. Hammar made the chemical analyses in the laboratory of the Division of Chemistry, United States Bureau of Standards, Washington, D.C., through the courtesy of the late E. W. Washburn, chief of the Division of Chemistry, who provided laboratory space and facilities.

A short summary of the results of the first season's work was published in May, 1933.[4]

F. M. Anderson kindly accompanied Trask in the field for a week and otherwise helped in many ways. R. D. Reed, of The Texas Company, generously furnished a detailed section of the sediments of the Shasta series exposed on McCarthy Creek, prepared by A. Gregersen and R. W. Burger of The Texas Company. J. M. Kirby, of the Standard Oil Company of California, spent a day with Trask in the field and assisted him greatly in the correlation of the sediments of the Chico formation. Acknowledgment is due G. C. Gester, of the Standard Oil Company of California, for his interest in the work and for granting permission to use data on the lithologic character and correlation of the Chico formation obtained by his company. Thanks are due Theo Crook, of the Standard Oil Company of California, for assistance in the field, and to E. K. Craig, of the Shell Oil Company, for information about oil seeps in the area. The writers wish to express their appreciation to Wm. C. Bates and Jasper W. Paulsen, Jr., of the Nigger Heaven Dome Oil and Gas Company, and to Walter Stalder, of the Buttes Oilfields, Inc., for their kindness in supplying information and core samples from the wells their companies have drilled.

The writers acknowledge gratefully the criticism of the manuscript by W. P. Woodring and H. D. Miser of the United States Geological Survey.

GEOLOGY OF AREA

General relations.—Late Mesozoic sediments, represented by the Shasta series of Lower Cretaceous[5] age and the Chico formation of Upper Cretaceous age, crop out in a belt 10 to 15 miles wide for more than 100 miles on the west side of the Sacramento Valley. This belt lies on the east flank of the northern Coast Ranges, 75–150 miles north-northeast of San Francisco. The general geographic relations of the belt are shown in Figure 1.

The Coast Ranges for a distance of 100–150 miles north of San Francisco consist chiefly of folded and faulted Mesozoic rocks, but in a few areas contain younger and older rocks. West of Red Bluff, in Tehama County, in the northern part of the area examined during the present investigation, the oldest rocks consist of quartzite, gneiss,

[4] P. D. Trask, "Results of the American Petroleum Institute Research Project on the Origin and Environment of Source Sediments," *Amer. Petrol. Inst. Prod. Bull. 211* (1933), p. 28.

[5] As discussed under *Shasta and Chico sediments*, the lower part of the Shasta series may be Upper Jurassic.

marble, and plutonic rocks of undetermined age, but presumably in part equivalent to Paleozoic formations of the Redding Quadrangle,

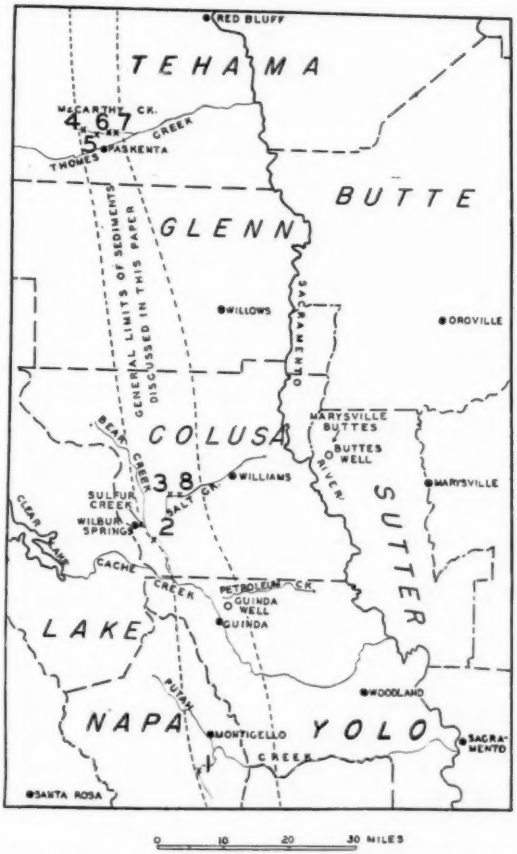

FIG. 1.—Index map of Sacramento Valley, showing location of samples studied.

described by Diller[6] and Hinds.[7] However, throughout most of the area studied, the oldest rocks consist of serpentine, sandstone, shale,

[6] J. S. Diller, *U.S. Geol. Survey Geol. Atlas, Redding Folio 138* (1906), pp. 2–5.

[7] N. E. A. Hinds, "Geologic Formations of the Redding-Weaverville Districts, Northern California," *California State Div. Mines, Rept. 29 of State Mineralogist* (1933), pp. 76–122.

and altered volcanics, corresponding in part with the Franciscan formation of questionable Jurassic age. The Franciscan rocks are overlain unconformably by the Shasta series, which in turn is overlain by the Chico formation. The sediments in this sequence of rocks consist mainly of clay, shale, sandy shale, and sandstone, and of minor amounts of conglomerate and limestone. The strata dip prevailingly more or less steeply east and are overlain unconformably by Pliocene terrestrial deposits having a maximum thickness of 2,000 feet.[8] The Shasta series and the Chico formation in the northern part of the area examined, apparently contain relatively few faults, but in the southern part they are somewhat faulted and folded, and in places the Shasta series rests against the Franciscan formation by fault contact.

Shasta and Chico sediments.—The Shasta and Chico sediments seem to have been deposited in a narrow geosyncline, the center of which corresponds nearly with the area discussed in this paper. The greatest thickness of the Shasta series is in the northern part of the area examined, near McCarthy Creek in Tehama County, where it is about 27,000 feet thick; and of the Chico formation, in the southern part of the area, in Yolo County, west of Woodland and along Putah Creek, where it is at least 13,500 feet thick. A thickness of 24,000 feet is reported for the Chico near Panoche Pass, 150 miles farther southeast,[9] but F. M. Anderson[10] regards part of the beds referred to the Chico in that area as belonging to the Shasta series.

The Shasta series and the Chico formation on the west side of the Sacramento Valley seemingly form a fairly continuous series of deposits. According to Diller and Stanton,[11] the Chico formation unconformably overlies the Shasta series, but in places, notably on Salt Creek west of Williams (Colusa County), the contact between the Shasta and the Chico seems to be gradational, as the sediments change gradually upward from shale through sandstone to conglomerate. The Shasta series on faunal evidence has been divided into the

[8] J. S. Diller and T. W. Stanton, "The Shasta-Chico Series," *Bull. Geol. Soc. America*, Vol. 5 (1894), pp. 438–44.
C. A. Anderson, "The Tuscan Formation of Northern California," *Bull. Univ. California Dept. Geol. Sci.*, Vol. 23 (1933), p. 235.

[9] R. Anderson and R. W. Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley, North of Coalinga, California," *U.S. Geol. Survey Bull. 603* (1915), p. 34.

[10] F. M. Anderson, "Knoxville-Shasta Succession in California," *Bull. Geol. Soc. America*, Vol. 44 (1933), p. 1263.

[11] J. S. Diller and T. W. Stanton, *op. cit.*, p. 452.

Knoxville formation below and the Horsetown formation above,[12] but in the section studied on McCarthy Creek (Tehama County) the lithologic character of the lower part of the Horsetown formation is similar to the lithologic character of the upper part of the Knoxville formation, and no change in character of the sediments was observed at the contact between the two formations. In this section the Knoxville is 19,000 feet and the Horsetown 8,000 feet thick.

Stanton[13] referred the Knoxville formation entirely to the Lower Cretaceous, but Anderson[14] and several other people, including J. P. Smith, place the lower part of the formation in the Upper Jurassic. Anderson proposes to restrict the name "Knoxville" to the lower part of the formation, use the name "Paskenta beds" for the upper part of the Knoxville, and limit the term "Shasta series" to beds he regards as of Lower Cretaceous age—that is, to the Paskenta beds of Anderson and the Horsetown formation. As the question of the age of the Knoxville formation has no direct bearing on the present discussion, the current assignment by the Geological Survey of Lower Cretaceous age to the Shasta series is followed in this paper and the entire Knoxville formation is included in the Shasta series. The Chico formation is regarded by all workers as Upper Cretaceous.

The Shasta series consists predominantly of shale throughout the area discussed in this report, but it also contains a significant proportion of thin-bedded sandstone (Fig. 2) and minor amounts of conglomerate and thin-bedded limestone and sandy limestone. The Shasta series, according to the data on the texture presented in Table I, consists of 10 per cent sandstone, 28 per cent sandy shale, and 62 per cent clay-shale. The shale as a rule is well sorted and has the texture of fine silt or coarse clay. In some parts of the Shasta series it consists of thin-bedded alternations of sandy shale and clay-shale. The sandstone layers in general are less than 6 inches thick, are fine-grained, and are somewhat poorly sorted. The limestone ordinarily is aphanitic and occurs in isolated layers less than 4 inches thick. The conglomerates are lenticular and attain a maximum thickness of about 200 feet. The pebbles ordinarily are less than one inch in

[12] J. S. Diller and T. W. Stanton, *op. cit.*, pp. 444–53.

[13] T. W. Stanton, "The Fauna of the Knoxville Beds," *U. S. Geol. Survey Bull. 133* (1895), p. 31.

[14] F. M. Anderson, "Jurassic and Cretaceous Divisions in the Knoxville-Shasta Succession of California," *California State Div. Mines Rept. 28 of State Mineralogist*, (1933), p. 320.

———, "Knoxville-Shasta Succession in California," *Bull. Geol. Soc. America*, Vol. 44 (1933), p. 1253.

J. P. Smith, "Salient Events in the Geologic History of California," *Science*, N. S., Vol. 30 (1909), p. 348.

diameter and the commonest rock type is a dark-colored rock that looks like chert.

A threefold division of the Shasta series has been adopted for presenting the data discussed in this paper—the lower part of the Knoxville formation, 14,000 feet thick; the upper part of the Knoxville, 5,000 feet thick; and the Horsetown formation, 8,000 feet thick. The lower part of the Knoxville formation consists predominantly of shale, except for a sandy zone that lies between 6,000 and 9,000 feet above the base of the formation. This sandy zone is composed of alternating sandy shale, clay-shale, and sandstone, and it culminates in a massive conglomeratic sandstone. The lower part of the Knoxville formation (Table I) consists of 3 per cent sandstone, 13 per cent sandy shale, and 84 per cent clay-shale. The upper part of the Knoxville formation represents all except the lower few hundred feet of Anderson's Paskenta beds. It consists of a sequence of alternating sandstone and sandy shale that grades upward into clay-shale, and is estimated to contain 22 per cent sandstone, 45 per cent sandy shale, and 33 per cent clay-shale (Table I). The Horsetown formation is composed of two lithologic members—a lower clay-shale member 3,500 feet thick, and an upper sandy shale member 4,500 feet thick. The formation is estimated to contain 14 per cent sandstone, and 43 per cent each of sandy shale and clay-shale (Table I). The lower shale member is indistinguishable lithologically from the underlying Knoxville formation, and the contact between the two formations has been placed at the position indicated by Anderson on faunal evidence.[15]

The Chico formation is much more sandy than the Shasta series. It consists predominantly of alternating sandstone, sandy shale, and clay-shale of varying thickness. The formation also contains minor amounts of conglomerate, especially near the base. Many of the sandstone layers are characterized by concretions that attain a maximum diameter of more than 2 feet. The sandstone in the lower 2,000 feet of the Chico formation on Salt Creek near Williams (Colusa County) consists largely of massive layers that form prominent ridges, but much of the sandstone in higher parts of the formation weathers readily and forms slopes similar to the slopes underlain by shale. The distribution of sand and shale varies in different areas. Near Red Bluff the Chico consists predominantly of sandstone,[16] but west of Williams, 100 miles to the south where the formation is thicker, it contains a large amount of shale. The Chico formation in the area

[15] F. M. Anderson, *op. cit.*, p. 1243.

[16] J. S. Diller and T. W. Stanton, *op. cit.*, p. 439.

near Williams and Woodland consists of 42 per cent sandstone, 36 per cent sandy shale or silt, and 21 per cent clay-shale (Table II). The proportion of sand in this area is the same in the upper and lower parts of the formation, but the percentage of clay-shale in the upper part of the Chico is greater than in the lower part, being 27 per cent in the upper part compared with 16 per cent in the lower part.

GENERAL ANALYSES

Sections examined.—Because of the great thickness of the formations, only one composite section of the Shasta series and the Chico formation was compiled. The samples representing the Shasta series were collected from McCarthy Creek (Tehama County); the lower part of the Chico formation from Salt Creek (Colusa County), 50 miles south; and the upper part of the Chico from the vicinity of Petroleum Creek (Yolo County), 20 miles farther south. In addition a few samples were procured from the upper part of the Chico near Marysville Buttes (Sutter County), on the east part of the floor of the Sacramento Valley, 25 miles east of Salt Creek.

The section of the Shasta series exposed on McCarthy Creek is fairly representative of the series, and it has the additional advantage of having been described recently by F. M. Anderson.[17] The exposures are good and the sediments are relatively unweathered. The thickness of the section was determined by Trask by a pace traverse and accords fairly well with the pace traverse of A. Gregerson and R. W. Burger, described by Anderson.[18] Significant details of the section and comparisons with Anderson's section are shown on Figure 2.

Samples were collected at intervals of 50–100 feet. In a few places, however, samples were taken every few feet in order to ascertain the variability of the sediments within the customary intervals of 50–100 feet. It was found in the places where samples were taken at small intervals that the sediments do not vary greatly in organic content. Approximately 350 samples were collected on McCarthy Creek. The character of the sediments is fairly uniform over large stratigraphic intervals and it is probable that the reliability of the work would not be increased greatly if double or treble the number of samples had been taken.

[17] F. M. Anderson, "Jurassic and Cretaceous Divisions in the Knoxville-Shasta Succession of California," *California State Div. Mines Rept. 28 of State Mineralogist* (1933), pp. 311–28.
———, "Knoxville-Shasta Succession in California," *Bull. Geol. Soc. America*, Vol. 44 (1933), pp. 1237–70.

[18] *Op. cit.*, pp. 313, 314.

of sorting of the sediments make it difficult to detect fine distinctions in texture.

A turbidity method has been found to aid the determination of the texture. A small, but definite, amount of the pulverized sediment is placed in one of the depressions of a porcelain spot plate, and a few drops of dilute (1 to 5) hydrochloric acid is added. After the effer-

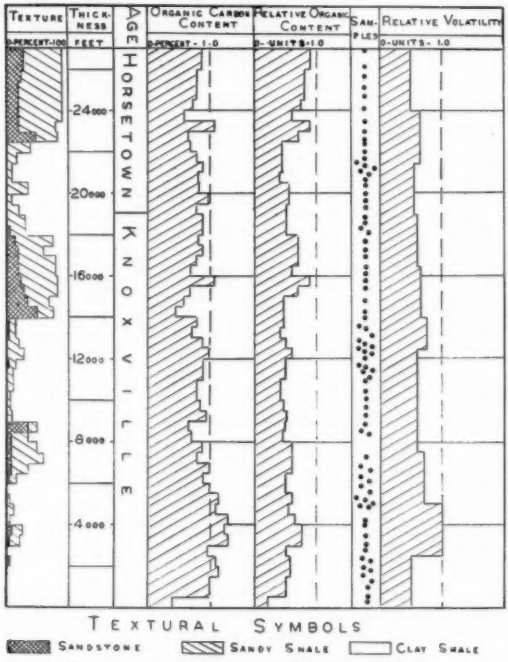

FIG. 4.—Organic content of Shasta sediments.

vescence, due to carbonates, has ceased, the texture is estimated from the turbidity by comparison with the turbidity of sediments of known texture. The method is not infallible and it requires a considerable amount of checking by more reliable methods, but despite these features it is very useful. In addition to aiding the determination of the texture, the method gives an index of the carbonate content of the sediments and also indicates the presence of oily substances in the sample.[24] If a sediment contains oily substances, the bubbles of

[24] P. D. Trask, H. E. Hammar, and C. C. Wu, *op. cit.*, p. 96.

carbon dioxide formed by the action of the acid become coated with oil. The coatings of oil tend to remain on the surface of the acid as opaque films after the bubbles collapse. Furthermore, the bubbles in oily samples are larger and less likely to break than in samples

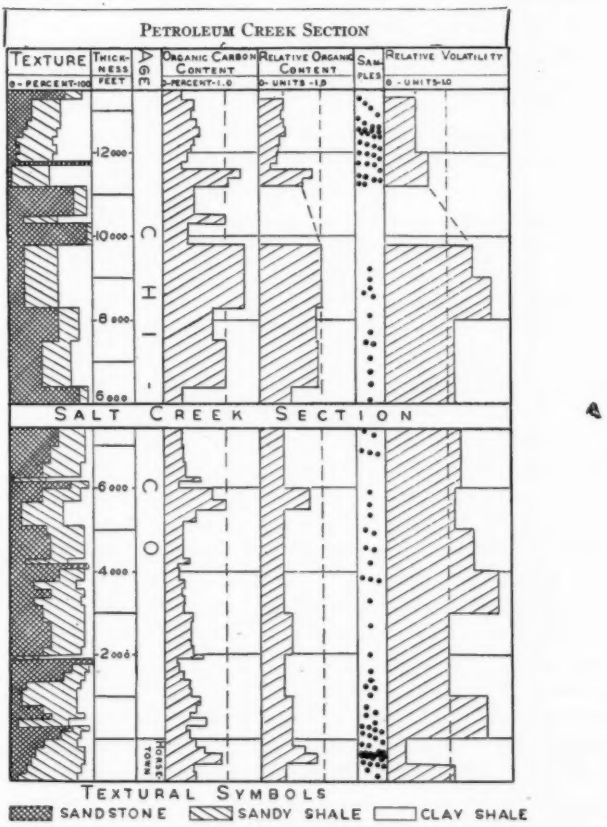

FIG. 5.—Organic content of Chico sediments. Petroleum Creek section.

that contain no oil. The oil films do not form in sediments that contain no carbonate. However, most sediments contain some carbonate and the presence of appreciable amounts of oil in many sediments can be detected by the failure of the acid to wet the particles or by the tendency of the particles to float on the surface of the acid. The

hydrochloric acid test, therefore, may be of value to geologists who wish to obtain clues as to the presence of oil in well or outcrop samples.

8. After the texture of these 125 samples had been ascertained, the relative organic content of the sediments was determined. The relative organic content represents the organic carbon content divided by a factor of 2.0 if the sample is clay, 1.0 if it is silt, and 0.5 if it is fine sand. Corresponding factors are used for intermediate textures. The basis for these factors is the observation that in the recent sediments in the Channel Islands the average organic content of the clays is twice the organic content of the silts, and the organic content of the silts is twice the organic content of the sands.[25] The same ratios for the organic content of clay, silt, and sand apply to the Pliocene sediments in the Sante Fe Springs oil field, but the relative organic content of the sediments at Santa Fe Springs is 1.0[26] compared with 1.6 in the recent sediments from the Channel Islands region.

The chief use of the relative organic content is to aid the determination of the organic content of strata of varying texture. In a sequence of alternating sands, sandy shale, and clay-shale, like these late Mesozoic sediments from northern California, the organic content of the sediments may not be indicated correctly by the average of the individual determinations of the organic content of samples taken at intervals through the section. For example, if the samples analyzed were chiefly clay-shale, and if silty shale predominated in the sequence of strata, the average organic content of the samples collected would be greater than the average organic content of the section represented by the samples, because clay-shale contains relatively more organic matter than silty shale. However, if the organic content of each sample were divided by an appropriate factor representing the influence of texture, the source of inaccuracy due to sampling and to variations in texture would largely disappear. The ratios so determined would indicate what the organic content of the sediments would be if the texture of all the sediments in the sequence of strata were uniform. That is, these ratios would represent the relative organic content. If the relative organic content were found to be constant or uniformly varying over large intervals, the organic content of any particular part of the section could be estimated by means of the texture. For example, if the relative organic content is 0.6 and the texture is clay, the organic carbon content would be 0.6×2.0 (the factor for clay) $= 1.2$ per cent.

[25] P. D. Trask, H. E. Hammar, and C. C. Wu, *op. cit.*, p. 77.
P. D. Trask, *op. cit.*, p. 27.

[26] P. D. Trask, *op. cit.*, p. 27.

The relative organic content is indicated for units of 500 feet in the Shasta series and 100 feet in the Chico formation (Figs. 4 and 5, Tables I and II). By the use of units of this size, several individual determinations are averaged for each zone, and irregularities due to inaccurate determination of the texture are minimized.

9. After the relative organic content of the sediments had been calculated, the distribution of sand, silt or sandy clay, and clay in the entire sequence of sediments was ascertained in order to determine the organic content by means of the relative organic content. This step in reality should be the first step, as the variations in texture of the sediments should be ascertained in the field as accurately as possible. In the work on these sediments, however, the importance of detailed field examinations of the texture was not realized at the time the field work was done, and the distribution of sand, silt or sandy clay, and clay was estimated in the office from notes taken in the field. The texture is indicated in three grades—sand, silt or sandy clay, and clay—in Figures 2 to 5 and in Tables I and II. In the preparation of the data, sediments of intermediate texture were allocated part to one texture and part to another; for example, a silt-clay would be 50 per cent silt and 50 per cent clay.

10. After the texture of the entire sequence of the Shasta and Chico sediments had been ascertained, the organic content was estimated for each unit of 100 feet in the Chico formation, and 500 feet in the Shasta series. The procedure was to multiply the relative organic content by the proper factor for the texture in each unit. For example if the percentages of sand, silt, and clay in a unit are 20, 30, and 50 per cent, respectively, the factor for the clay is $20\times 2=40$, for the silt $30\times 1=30$, and for the sand $50\times 0.5=25$. The sum of these factors is $40+30+25=95$, which is the factor for the texture in that zone. If the relative organic content is 0.55, the organic carbon content of the interval is $0.95\times 0.55=0.5$. Because of difficulty of determining small distinctions of texture, the data on the organic carbon content are reported to the nearest tenth or twentieth of a per cent (Figs. 4 and 5, and Tables I and II).

11. The data on the organic content are presented in terms of organic carbon, because organic carbon is a tangible quantity that can be measured directly or estimated with a fair degree of accuracy. The total organic content, however, can not yet be determined directly with satisfactory reliability. Carbon forms about two-thirds of the organic content, and hydrogen, oxygen, nitrogen, sulphur, phosphorus, et cetera, the other one-third. The proportion of these different elements varies somewhat in different types of organic matter, but it is

presumed that the percentage of carbon in the organic content of ancient sediments, on the average, is approximately 67 per cent.[27] That is, the organic content is approximately 1.5 times the organic carbon content.

Results.—The results of the study of the sediments in the composite section of the Shasta series and the Chico formation are presented in Figures 2–5, and summaries of the results are given in Tables I and II. The organic content of the sediments is low and fairly uniform throughout the entire section, especially in the Shasta series. The average organic carbon content of the Shasta series is 0.87 per cent. The maximum for any 500-foot zone is 1.3 per cent, and is between 3,000 and 4,000 feet above the base of the series. The minimum for any 500-foot zone is 0.45 per cent, and is situated in the sandy beds at the bottom of the upper part of the Knoxville formation, 14,000 feet above the base of the Shasta series.

The organic content of the Chico formation is smaller than the organic content of the Shasta series, but because of the greater variation in texture, it is more variable than that of the Shasta series. The average organic carbon content of the lower 7,400 feet of the Chico on Salt Creek is 0.42 per cent and of the upper 2,300 feet on Petroleum Creek is 0.55 per cent; but in the Guinda well, near Petroleum Creek, in the lower 4,000 feet of the upper part of the Chico, it is 1.0 per cent.

The samples from the upper part of the Chico on the south side of Marysville Buttes contain more clay shale and have a higher organic content than the sediments on the west side of the Sacramento Valley. The outcrop samples from the upper 2,000 feet of the Chico at Marysville Buttes contain 0.9 per cent organic carbon, and the core samples from the Buttes well, at Marysville Buttes, which presumably represent a slightly lower horizon, contain 1.4 per cent organic carbon. The higher organic content of the well samples may be due to the unweathered nature of the sediments.

The relative organic content of the Shasta series is low and in the lower 23,000 feet is fairly uniform, but in the upper 4,000 feet it increases gradually upward. The average for the Shasta series is 0.56; the maximum is 0.8 and occurs in the upper 3,000 feet of the Horsetown formation. The minimum is 0.4 and is in the lower part of the Knoxville formation, 10,000–11,000 feet above the base of the Shasta series. However, in the lower 500 feet of the series, as indicated by a single sample, it is 0.2.

The relative organic content of the outcrop samples from the

[27] P. D. Trask, H. E. Hammar, and C. C. Wu, *op. cit.*, p. 18.
P. D. Trask, *op. cit.*, pp. 24, 27.

TABLE I

GENERAL FEATURES OF SHASTA SEDIMENTS

Feet Above Base	Sand	Sandy Shale	Shale	Estimated Organic Carbon	Relative Organic Content	Coefficient of Volatility	Bitumen	Number of Samples		
	Per Cent							Assay	Nitrogen	Carbon
HORSETOWN FORMATION										
24,000–27,000	24	66	10	.8	.8	.5	.03	32	6	1
21,500–24,000	18	45	37	.8	.6	.65	.04	42	5	1
19,000–21,500	0	17	83	.85	.45	.55	.08	48	10	2
Average	14	43	43	.82	.61	.57	.05	122*	21*	4*
UPPER PART OF KNOXVILLE FORMATION—ANDERSON'S PASKENTA BEDS										
16,500–19,000	12	43	45	.85	.6	.6	.11	29	8	3
14,000–16,500	32	47	21	.7	.65	.65	.05	28	6	2
Average	22	45	33	.78	.63	.63	.08	57*	14*	5*
LOWER PART OF KNOXVILLE FORMATION										
12,500–14,000	5	12	83	.8	.45	.75	.08	25	8	2
10,000–12,500	1	14	85	.9	.5	.6	.03	34	12	3
7,500–10,000	4	19	77	.85	.5	.6	.02	25	5	2
5,000– 7,500	5	19	76	.95	.55	.7	.02	31	10	2
2,500– 5,000	3	9	88	1.2	.65	1.0	.03	24	8	3
0– 2,500	1	0	99	.9	.45	.5	.04	25	8	2
Average	3	13	84	.93	.51	.7	.03	164	51	14
General Average	10	28	62	.87	.56	.65	.05	343*	86*	23*

* Total number of samples.

Chico formation likewise is low and uniform. The average of both the lower part of the formation on Salt Creek and the upper 2,300 feet on Petroleum Creek is 0.43, which is significantly lower than the average of 0.56 for the Shasta series. As the Chico sediments seem to be weathered more than the Shasta sediments, this lower relative organic content in the Chico outcrop samples may not reflect a lower relative organic content in the unweathered state. The maximum relative organic content in the Chico is 1.0 and is located in the upper 2,000 feet represented by samples in the Guinda well.

The coefficient of volatility likewise is fairly uniform throughout the entire section, but in the Shasta series it is only half what it is in the Chico formation; the average for the Shasta series is 0.65 and for the Chico formation 1.2. The coefficient of volatility is approximately the same in well and outcrop samples in the Chico formation. In the samples from Marysville Buttes it is only 0.3, perhaps because of the igneous activity in the region.

The bitumen content throughout most of the section is low, but insufficient analyses were made to indicate the distribution in detail. The average for the Shasta series is 0.05 per cent and for the lower part of the Chico formation, 0.03 per cent. The bitumen was not measured in the upper part of the Chico. The maximum is 0.11 per cent and occurs in two places: one, in the upper part of the Knoxville formation, 16,500–19,000 feet above the base of the Shasta series, and the other, in the lower 1,000 feet of the Chico formation. The upper 5,000 feet of the lower part of the Chico on Salt Creek contains less than 0.02 per cent bitumen, and the upper 5,000 and the lower 12,000 feet of the Shasta series on McCarthy Creek contain from 0.02 to 0.04 per cent.

The outstanding feature of the Shasta and Chico sediments, aside from variations caused by texture, is the uniform organic content of the sediments. Very few zones differ materially from the average. The lower 500 feet of the Shasta series is characterized by a low relative organic content. The zone 2,500–5,000 feet above the base of the Shasta has a comparatively high organic content, high relative organic content, and high coefficient of volatility, but it does not have any correspondingly high bitumen content. The bitumen content in the interval between 12,000 and 21,000 feet above the base of the Shasta series is comparatively high, but is not high compared with sediments from other regions. The relative organic content of the upper 4,000 feet of the Shasta series is 40 per cent greater than that of the underlying sediments, but as the texture of the sediments in his zone is coarser the organic content is approximately the same.

The bitumen content of the lower 500 feet of the Chico is comparatively high, and may have some connection with the oil seeps in the upper part of the Horsetown formation, 375 feet below the base of the Chico. The organic content of the lower 500 feet of the Chico formation, however, does not seem to be different from the remainder of the Chico. The richest part of the Chico on Salt Creek is a shale zone 5,500–6,000 feet above the base, where the relative organic content is 0.8 and the organic carbon content 0.9 per cent. The coefficient of volatility and bitumen content, however, are not correspondingly high in this zone. The organic content of the upper 2,300 feet of the Chico on Petroleum Creek is low and is only a little more than half the organic content of the upper 2,000 feet of the Chico on the south side of Marysville Buttes. The samples from Marysville Buttes, however, may not represent the same part of the Chico. The sediments from Marysville Buttes possess the further distinction of having a very low coefficient of volatility. The core samples from the wells drilled in the upper part of the Chico, as mentioned previously, are characterized by their comparatively high organic content; but the volatility of the core samples is no higher than in adjoining sediments.

DETAILED ANALYSES

Method of analysis.—The carbon, nitrogen, and volatility determinations, though indicating the general nature of the organic constituents, afford few criteria for ascertaining the real character of the organic matter. Therefore, in order to ascertain something about the character of the organic matter in these late Mesozoic sediments, eight samples were analyzed in detail by a procedure similar to one used for recent sediments.[28] The method consists of a series of successive extractions of the sediments with carbon tetrachloride, hot water, ethyl alcohol, acetone, dilute sulphuric acid under steam pressure, and a hot 4 per cent solution of sodium hydroxide. Carbon, nitrogen, and the relative state of oxidation (as indicated by the amount of chromic acid reduced) are determined in each of the extracts and in several of the residues. This procedure splits the organic content into a large number of components, with the result that similarities and differences in the general character of the organic content of different sediments are determined. The method of analysis has certain objectionable features, which will be discussed in full in a later paper; but it seems to be the best method now available

[28] P. D. Trask, H. E. Hammar, and C. C. Wu, *op. cit.*, pp. 185–08.

TABLE II

GENERAL FEATURES OF CHICO AND UPPERMOST HORSETOWN SEDIMENTS

Feet Above Base	Sand	Sandy Shale	Shale	Estimated Organic Carbon	Relative Organic Content	Coefficient of Volatility	Bitumen	Number of Samples		
	Per Cent							Assays	Nitrogen	Carbon
PETROLEUM CREEK SECTION—CHICO FORMATION										
13,300–13,500	70	20	10	.3?	—	—	—	0	0	0
12,200–13,300	23	39	38	.5	.4	.5	—	16	12	12*
11,200–12,200	12	43	45	.65	.47	.7	—	17	17	17
10,000–11,200	73	17	10	.5?	—	—	—	0	0	0
9,000–10,000	35	33	32	1.15	1.0	1.4	—	2	2	2
8,000– 9,000	32	36	32	1.15	1.0	1 7	—	4	4	4
7,000– 8,000	50	30	20	.85	.9	1.1	—	4	4	4
6,000– 7,000	58	25	17	.7	.8	1.1	—	3	3	3
Average	42	31	27	.8	.75	1.1	—	46‡	42‡	42‡
SALT CREEK SECTION—CHICO FORMATION										
6,000– 7,400	50	36	14	.35	.4	1.2	.01	11	5	3†
5,000– 6,000	26	48	26	.65	.6	1.1	.02	6	4	1
4,000– 5,000	51	38	11	.3	.35	1.4	.02	17	5	3
3,000– 4,000	42	45	13	.3	.35	1.8	.02	8	3	2
2,000– 3,000	46	43	11	.45	.5	1.0	—	9	2	0
1,000– 2,000	45	38	17	.35	.4	1.0	.06	15	5	3
0– 1,000	37	44	19	.5	.5	1.6	.11	16	12	5
Average	43	41	16	.42	.45	1.3	.03	82‡	36‡	17‡

TABLE II (*Continued*)

GENERAL FEATURES OF CHICO AND UPPERMOST HORSETOWN SEDIMENTS

Feet Above Base	*Sand*	*Sandy Shale*	*Shale*	*Estimated Organic Carbon*	*Relative Organic Content*	*Coefficient of Volatility*	*Bitumen*	*Number of Samples*		
	Per Cent							*Assays*	*Nitrogen*	*Carbon*
Feet Below Top	SALT CREEK SECTION—HORSETOWN FORMATION									
0– 370	35	50	15	.6	.6	.3	—	10	8	8*
370– 600	25	65	10	.9	.9	.3	—	11	11	11
600– 1,000	15	68	17	.45	.4	1.0	—	3	3	3
Average	25	60	15	.6	.6	.6	—	24‡	22‡	22‡
	MARYSVILLE BUTTES SECTION—CHICO FORMATION									
0– 1,000	10	40	50	.75	.5	.3	—	8	8	8*
1,000– 2,000	5	40	55	1.0	.65	.3	—	12	11	11
Depth—Feet	BUTTES WELL NO. 1—CHICO FORMATION									.....
250– 2,154	2	44	54	1.4	.9	.3	—	8	6	6*

* Carbon estimated by chromic acid method in this section.
† Carbon determined by potassium permanganate method in this section.
‡ Total number of samples.

and it gives much information about the nature of the organic constituents of sediments.

Location of samples.—Because of the length of time required for the analyses, only eight samples could be studied. Five of these samples were selected from different parts of the Shasta series and the Chico formation, and three from the vicinity of oil seeps (Figs. 1, 3 and 5). Such a choice of samples makes it possible to compare sediments in the general section with samples from seeps that presumably are potential source beds. Five samples, however, are scarcely enough to represent adequately 40,000 feet of strata.

Oil seeps have been known for many years from several places in northern California.[29] The three seeps that were chosen for study are located near the base of the Shasta series in the bed of a creek in Napa County, 4 miles south of Monticello on the west side of the road to Napa, and 1 mile north of the junction of the road to Rutherford (sample 1); in serpentine along a line of faulting on the west side of the bed of Bear Creek in Colusa County, 0.5 mile west of where the Williams-Clear Lake highway crosses Bear Creek (sample 2); and in the upper part of the Shasta series, 375 feet below the top of the Horsetown formation in the bed of Salt Creek about 10 miles west of Williams, in Colusa County, on the highway to Clear Lake (sample 3). An amber-colored oil having a very persistent pungent odor was observed at the seeps on Bear and Salt Creek, but no oil was seen at the seep near Monticello. However, from the appearance of the ground at the place where the seep is reported and the presence of oil in wells drilled a short distance down the dip from the seep, there is little reason to doubt the existence of a seep.

At the seep on Salt Creek oil oozes from the upturned edges of a zone of thin-bedded alternating sandstone, sandy shale, and clay-shale in three places over an interval of 25 feet. In addition a small amount of gas emerges from the creek bed 100 feet stratigraphically below the lowest oil seep. Several wells, 500–900 feet deep, located a few hundred feet east of the seeps, have produced a very small quantity of oil which commands a high price, as it is reputed to contain ichthyol.

The organic content of a number of samples in the vicinity of

[29] G. F. Becker, "Geology of the Quicksilver Deposits of the Pacific Slope," *U.S. Geol. Survey Mon. 13* (1888), pp. 367–75.
C. L. Watts, "Oil and Gas Yielding Formations of California," *California State Min. Bur. Bull. 19* (1900), pp. 159–66.
R. P. McLaughlin and G. A. Waring, "Petroleum Industry of California," *ibid., Bull. 69* (1914), pp. 441–42.
L. Vander Leck, "Petroleum Resources of California," *ibid., Bull. 89* (1921), p. 52.

this zone of seeps in the upper 1,000 feet of the Horsetown formation was determined (Table II and Figs. 3 and 5). The seeps are located in a zone of comparatively rich organic content. The sediments in this zone contain considerably more organic matter than the sediments above and below the seeps, and the change from high to low organic content on the two sides of the zone of seeps is abrupt. The average organic carbon content of the sediments in the zone of seeps is 0.9 per cent, compared with 0.6 in the sediments above, and 0.4 per cent in the sediments below. The organic content of the uppermost 350 feet of the Horsetown formation above the seeps does not differ greatly from the organic content of the overlying Chico formation.

Two of the three samples (1 and 3) from the seeps occur in steeply dipping, apparently unfaulted, somewhat silty clay-shale, out of which oil oozes. In addition, oil has been encountered in the projection of the strata in wells located down the dip. There is a strong presumption, therefore, that the samples from these seeps are analogous to the sediments that generate the oil at the seeps. The third sample (2) comes from a block of shale, downfaulted into serpentine. The shale is well bedded, is partly altered, dips 90°, and has the texture of a somewhat silty clay. The locality is in a highway cut, 75 feet above, and 125 yards southwest of, the seep; but because of the similarity in character of organic content of this sample and sample 3 from the upper part of the Horsetown formation on Salt Creek, and also because of the similarity in appearance of the oil at the two seeps, there is a fairly strong suggestion that this sample, like samples 1 and 3, is analogous to the sediments that generated the oil at the seep.

The age of the strata at this locality, on Bear Creek, is problematical. Oil seeps, associated with faulting, are found at intervals along the valley of Bear Creek northward for 3 miles. About 0.25 mile north of the mouth of Sulfur Creek, a seep is associated with beds correlated by Anderson[20] as belonging to his Knoxville series—that is, to the lower part of the Knoxville formation as classified in this paper. The shale from which sample 2 was obtained, 3 miles below this locality, is roughly in the projection of the strike of the Knoxville beds, and may also belong to the Knoxville formation, but because of faulting in the intervening area, the correlation is questionable.

The general section of the Shasta series and Chico formation is represented by five detailed analyses. Samples 4, 5, 6, and 7 come from successively higher parts of the Shasta series on McCarthy

[20] F. M. Anderson, personal communication.

Creek, and sample 8 comes from near the top of the lower part of the Chico formation on Salt Creek. The stratigraphic location of the samples is indicated on Figures 2 and 3. All the samples are fairly well-sorted, somewhat silty clay-shale. Sample 4 comes from the zone of comparatively high organic content, lying about 4,300 feet above the base of the Knoxville and 200 feet below a conglomerate. This conglomerate crops out at a spring 300 feet west of the house near the head of the south fork of McCarthy Creek. Sample 5 was obtained near the top of the lower part of the Knoxville formation, 13,400 feet above the base of the formation, about 150 feet west of a bridge across the creek. Sample 6 represents a horizon in the lower part of the Horsetown formation, 21,200 feet above the base of the Shasta series. The locality is in a shale bank on the east side of the Paskenta-Lowry road, just north of the bridge across McCarthy Creek. Sample 7 is from the upper part of the Horsetown formation, 26,100 feet above the base of the Shasta series at a sharp bend in the creek, between the house and the large tributary that enters from the north. Sample 8 comes from the richest part of the Chico formation on Salt Creek, in a shale bank along the highway, 60 feet stratigraphically above a conglomerate, 5,000 feet above the base of the Chico.

Results.—As the analyses need to be corrected for certain factors that have not yet been determined adequately, the final results are not given in this paper. Sufficient data, however, are available to prepare a table (Table III) showing the general relationship of the samples to one another. In this table the samples are arranged in rows to show the relationship of each sample to each of the other seven samples, on the basis of five increasingly different degrees of similarity. It is probable that when the results of the analyses are ultimately compiled, some of the pairs of sediments may be shifted from one column to an adjoining column, but it is not probable that many pairs will be shifted more than one column. The table therefore should indicate the general relationship between the samples.

The striking feature about the eight samples analyzed in detail is the similarity between all the samples from the general section and the dissimilarity between the sediments from the general section and the sediments from the oil seeps (Table III). Samples 4, 5, 6, and 7, representing successively higher horizons in the Shasta series, resemble one another fairly closely, though the character of the organic content apparently changes gradually upward in the section. Sample 4 resembles samples 5 and 6 more than it does sample 7, and it resembles sample 7 much more than it does sample 8. Similarly, the

samples most closely related to sample 8 are samples 3, 5, 6, and 7, which are the samples located stratigraphically nearest to sample 8. Sample 8, however, has several distinctive features, which separate it from these four samples. Sample 5 is unique in possessing several of the characteristics of the other seven samples.

The samples from the oil seeps are fairly different from the samples in the general section, with the exception of sample 5. Sample 1, from the lower part of the Knoxville formation near Monticello, is

TABLE III

RELATIONSHIP BETWEEN ORGANIC CONSTITUENTS OF SEVERAL REPRESENTATIVE SHASTA AND CHICO SEDIMENTS

A	*Degree of Relationship to Samples in Column A*				
	High	*Fairly High*	*Intermediate*	*Fairly Low*	*Low*
	Samples				
1		6	5	7	2, 3, 4, 8
2	3	5	4, 6	7, 8	1
3	2	5	8	4, 6, 7	1
4	5, 6	7	2	3	1, 8
5	4, 6, 7	2, 3, 8	1		
6	4, 5, 7	1	2, 8	3	
7	5, 6	4, 8		1, 2, 3	
8		5, 7	3, 6	2	1, 4

LOCATION OF SAMPLES

1. Oil seep near base of Knoxville formation near Monticello.
2. Associated with oil seep from serpentine on Bear Creek. Strata presumably from lower or middle part of Shasta series.
3. Oil seep near top of Horsetown formation on Salt Creek.
4. Lower part of Knoxville formation on McCarthy Creek 4,200 feet above base.
5. Upper part of Knoxville formation on McCarthy Creek, 13,400 feet above base.
6. Lower part of Horsetown formation on McCarthy Creek, 21,200 feet above base of Knoxville.
7. Upper part of Horsetown formation on McCarthy Creek, 26,100 feet above base of Knoxville.
8. Central part of Chico formation on Salt Creek, 5,000 feet above base of Chico.

distinct from the other two samples from the seeps. Its closest relatives are samples 5 and 6 in the upper part of the Knoxville in the general section. Sample 2, from the vicinity of the seep on Bear Creek, is fairly closely related to sample 3, from the upper part of the Horsetown formation on Salt Creek. Both these samples resemble sample 5 from the general section and sample 3 has several

of the characteristics of sample 8, lying 5,000 feet above in the Chico formation.

INTERPRETATION

As stated in the introduction, little is yet known about the significance of the data with respect to the possibilities of the sediments as source beds. In addition, the present investigation is only a preliminary study. Furthermore, it would be desirable to have made more than eight detailed analyses, and the effect of weathering should be understood more fully. However, despite these features, nearly all the results lead to an unfavorable consideration of the sediments as source beds.

1. The organic content of the sediments is low. It seems evident that a low organic content can not be considered as a favorable indication of the possibilities of the sediments as source beds, because, in general, the less organic matter a sediment contains, the smaller are its chances of being a source bed. Naturally, it is entirely possible for sediments of low organic content to be favorable source beds, for though the total organic content may be low, the proportion of oil-generating substances may be high. The Pliocene sediments in the Santa Fe Springs oil field, which seem to be good source beds, have an average organic carbon content of 1.0,[31] which is only a little greater than the average of 0.87 per cent for the Shasta series. The sediments at Santa Fe Springs, however, differ from the Shasta and Chico sediments in having a much greater relative organic content. The relative organic content of the sediments at Santa Fe Springs is 1.0[32] compared with about 0.6 in the Shasta series and the Chico formation. Furthermore, the low organic content of some ancient sediments may be low because of the loss of organic matter since the sediments were first deposited, either by chemical changes while the sediments were buried or by weathering. However, unless there is evidence to show that the initial organic content was greater, or that the proportion of oil-generating substances in the sediments is high, a small organic content can not be interpreted as a favorable indication of the possibilities of the sediments as source beds.

2. The difference between the character of the organic matter in the sediments from the oil seeps and that of the sediments in the general section suggests that sediments of the type that generate the oil at the seeps are not widely distributed throughout the general section. The comparative scarcity of oil seeps in the area under dis-

[31] P. D. Trask, *op. cit.*, p. 27.

[32] *Ibid.*

cussion supports this inference. The apparent paucity in the general section of sediments of the type that seem to generate the oil at the seeps, when considered by itself is not a favorable indication of the presence of source beds in the general section; but it is possible, nevertheless, that the sediments in the general sequence of strata, though differing in character from these sediments from the seeps, may also be source beds. Furthermore, five samples can scarcely represent adequately 40,000 feet of strata.

3. The uniformity in quantity and character of the organic matter in the sediments in the general section leads to the inference that almost any part of the Shasta series or the Chico formation is about as favorable for source beds as any other part. Consequently, if oil is found subsequently in any part of the section, it would seem, according to the data now available, that almost any other part would be as likely to contain favorable source beds as the part that generated the oil. However, the failure to find oil in commercial amounts in the wells that have been drilled to date, when considered in the light of the uniformity of the organic content of the sediments, is not a heartening indication of the presence of favorable source beds of petroleum in this area. The inference about the uniformity of the organic content, however, is more encouraging with respect to source beds of gas, because significant quantities of gas have been reported from the Buttes well No. 1 of the Buttes Oilfields, Inc., and from the Guinda well of the Nigger Heaven Dome Oil and Gas Company.

The Shasta series, because of its greater organic content, smaller quantity of sand, and closer relationship to the samples from the seeps, seems to offer greater possibilities as source beds than the Chico; but parts of the Chico, notably the shaly zone 5,000–6,000 feet above the base of the Chico and the shales in the Guinda and Buttes wells, are as rich as the Shasta sediments. The shale 2,500–5,000 feet above the base of the Knoxville formation is the richest part of the Shasta series, and may represent a more favorable part of the section.

The data therefore give rise to an inconclusive interpretation of the possibilities of the sediments as source beds. The low organic content and the differences between the sediments from the general section and from the seeps are not encouraging indications of the presence of favorable source beds, but, on the other hand, none of the data indicates that adequate source beds for an oil field can not be present. The most reliable inference resulting from the work, is that, with the possible exception of some sandy zones, almost any part of the Shasta series or the Chico formation offers about the same possibilities as source beds as any other part.

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REVIEWS AND NEW PUBLICATIONS

Lehrbuch der angewandten Geophysik. Geophysikalische Aufschlussmethoden (Textbook of Applied Geophysics. Geophysical Methods of Exploration.) By HANS HAALCK. Gebrüder Borntraeger, Berlin (1934). 376 pp., 142 figs., 6 pls. 6×9 inches. Paper, 24 RM.; cloth, 26 RM.

This is an elementary textbook of applied geophysics. Its appeal will be to geologists who wish to become acquainted with geophysical methods, to geologist-geophysicists who wish to become conversant with methods of interpretation of geophysical data, and to field men in geophysics who desire a better understanding of the principles underlying the different methods of exploration.

There are five chapters. The first deals with gravitational methods, the second with the magnetic method. Electrical methods are discussed in the third chapter, and the seismic method in the fourth. The fifth chapter deals with the radioactive method; at the end of this chapter the author discusses a number of additional methods which have not yet found extensive application.

Two-thirds of the first chapter are devoted to the torsion balance; the instrument is discussed in detail and the meaning of the quantities measured explained. Adequate directions are given for the correction of the observations and for the interpretation of the corrected data. There is a meager discussion of pendulum work; four pages are devoted to a description of the static gravity meters of Ising and Urelins, Holweck and Lejay, and Haalck. In the reviewer's opinion, pendulum measurements deserved more space.

The second chapter, on the magnetic method, covers the subject adequately and is well written.

The treatment of electrical prospecting in the third chapter is comprehensive and includes all of the better known methods.

After reading a few pages of the fourth chapter one is inclined to look on the title-page and at the end of the preface for the year of publication; that one could find a book published in 1934 on applied seismology which devotes only 5 out of 57 pages to reflection shooting is rather hard to believe. On page 341 it is stated that the method is being used very rarely; on page 345 the best shotpoint-receiver distance is given as 5/4 to 9/4 of the depth of the reflecting layer. According to page 305, the reflection method can be used only on ice and in sea sounding, because the direct waves so obliterate the reflections that the latter can be recognized only under the most favorable conditions. Nearly 4 pages are wasted on a futile discussion of the perpendicular, or inclined, or bent ray in refraction shooting. It is doubtful if anybody would follow the text if refraction shooting were done now; the author writes from the viewpoint current about 1926, and 8 years is a long time in geophysics.

The radioactive method is discussed in a satisfactory manner in the fifth chapter, but it should be stated emphatically that (p. 353) alpha rays are *not* identical with canal rays.

Very comprehensive bibliographies are included with each chapter; the value of these can hardly be overestimated.

The volume is well worth reading and studying.

L. W. BLAU

HOUSTON, TEXAS
August 19, 1934

Aufsuchung von Wasser mit Geophysikalischen Methoden (Prospecting for Water with Geophysical Methods). By J. KOENIGSBERGER. Akad. Verlagsgesellschaft M.B.H., Leipzig (1933). 63 pp., 22 figs. 5.75×8.75 inches. Paper. Price, M. 3.80.

The chapter headings of this book include "Geophysical Points of View," "General Remarks on Geoelectrical Methods in Hydrology," "Principal Geoelectrical Methods in Hydrology," "Auxiliary Electrical Methods," "Electrical Waves in Hydrology," and "Other Auxiliary Methods."

A survey for water by geophysical methods requires preliminary study of climate, hydrology, and geology of the country. It is desirable that the work start from some water well so that the geophysical measurements obtained may be evaluated in terms of water sands. In the preliminary work different types of electrical methods should be tried, inasmuch as no one method is most successful in all cases.

Electrical methods are used almost exclusively in the search for water. It is suggested in the text that seismograph and torsion balance may be used in an auxiliary manner in attempting to evaluate the results of the electrical survey.

Successful attempts have been made not only in locating water but in reading, in the results obtained, the probable purity of the water. It may be possible to determine the quantity of water available from the probable porosity of the water-bearing stratum.

A number of figures are given showing actual curves obtained by the electrical methods plotted against well logs.

The publication of actual field measurements by the various electrical methods and the discussion of these results in the light of subsequent test holes makes this book of interest to the practical geophysicist.

L. Y. FAUST
GEOPHYSICAL RESEARCH CORPORATION

TULSA, OKLAHOMA
August 30, 1934

Geological Map of the Republic of Austria and Neighboring Territory. Compiled by HERMANN VETTERS. Geologische Bundesanstalt, Vienna III, Rasumofskygasse 23. Price: paper, 60 Schillings.

This map, which was offered for sale late in 1933 by the Geologische Bundesanstalt, Vienna III, Rasumofskygasse 23, was compiled by Dr. Hermann Vetters from 1:750,000-scale draught prepared in 1922–23 by members of the Geologische Bundesanstalt. The map is a carefully revised two-sheet edition, scale 1:500,000, printed on good paper with excellent color scheme, well chosen type, and legend very conveniently arranged. It is set up in the German language. The colored part of the combined sheets is 125 centimeters

long and 90 centimeters wide. The ordinary map costs 60 Schillings. The wall map costs 80 Schillings and if copies mounted on linen for field work are desired they may be had at 74 Schillings. A text to accompany the map will be issued in September or October, 1934, giving the lists of place names et cetera in the different languages. There will also be included a list of errors and some data on the sources of material.

The area covered by the map is about 270,000 square kilometers or 260 of the special sheets of the grid commonly used on the Continent. Its northern boundary extends through Ansbach, Klattau, Gross-Meseritsch, and Kremsier; its eastern edge through Waag, Neustadtl, Raab, and Varoslöd; its southern, a broken one, through Agram, Fiume, Padua, and Lodi; and its western limits are Stuttgart, St. Gallen, and Traviglis. Within these generous boundaries lie the whole of the Eastern Alps with both their north and south forelands, parts of the Swabish-Frankish "Alb" and of the Bohemian Granite zone, the projection of the Alps into the Little Carpathians, a large part of the western or Little Hungarian Plain with part of the Bakony Mountains, and a large area of the Croatian Plain of Yugoslavia.

The map, which is a 1:500,000-scale polygonic projection made from the 1:200,000-scale general map of Central Europe, is divided into degrees Ferro with degrees Greenwich marked along the margins.

At the lower right-hand corner is a finding map, scale 1:3,850,000, which serves more particularly to show at a glance the sources of material used in compiling the geological boundaries and subdivisions. In some ways this is a very important feature of the edition because in assembling the data from the various political divisions represented, some maps lacking revision since 1850 had to be used, though in other areas up-to-date information was available. The editor is to be commended for his excellent work in joining this mosaic of varying degrees of map accuracy and detail into a whole of surprising uniformity.

It is evident that the European geologist has mapped the more rugged and mountainous areas with their complex structure problems in much greater detail than he did the plains with their margins of upland. Consequently, the map presents an excellent picture of the major geologic feature of the mountain ranges, though the geologist interested in the Tertiary basins will find less detail and refinement in the subdivisions of formations. There is, however, more detail given than is usual on maps of 1:500,000 scale and the accuracy of position of the formation boundaries, towns, et cetera, makes it a useful base for enlargements or reductions.

The color scheme used follows in a general way that of the international geologic map of Europe. It brings out essential features as the geologist is accustomed to picture them, and the contrasts provided also depict the great topographic provinces. Since its wealth of detail is essentially geological (75 color and symbol distinctions with 50 letter differentiations are used), little in the way of culture could be added. Few structural features are noted and developed mineral deposits are not marked. Elevations of towns and of mountain peaks are scattered very conveniently, particularly in the Alpine region.

Great care was taken in printing and correcting the map. The off-set method of printing was used. The formation boundaries were placed on stone and the remaining details on aluminium, these having required in all 20 plates. The task of checking and correcting errors was a difficult one, more than

5,000 changes, most of them very small, being necessary before the final edition was issued.

The map is to be recommended to schools and libraries as the best of its kind in Central Europe.

WALTER M. SMALL

VIENNA, AUSTRIA
August 21, 1934

Compilacion de los Estudios Geologicos Oficiales en Colombia—1917 a 1933, Tomo I (Compilation of the Official Geological Studies in Colombia, 1917 to 1933, Vol. I). By ROBERTO SCHEIB. Edited by George A. Perry, chief engineer of the Technical Division of the Department of Mines and Petroleum. Published by: Jefe de La Sección de Publicaciones, Belisario Vejarano S., Bogata Colombia—Imprenta Nacional (1933). 475 pp., 79 figs., 9 maps in pocket.

This volume is the first of five to be published by the Colombian government, covering official work done by various geologists under the authority of the National Scientific Commission, which was organized in 1916, under the direction of the late Robert Scheibe, formerly of the Geological Service of Prussia.

Some of these papers had appeared previously, in imperfect form, in various pamphlets of the Scientific Commission, bulletins of Mines and Petroleum, memorials to Congress, and Ministerial reports, but these are widely scattered and inaccessible, and many of them, having been written by foreigners, with imperfect knowledge of the Spanish language, are full of grammatical errors. Many of these deficiencies have been corrected by the present editor. Subsequent volumes will be the following. Volume II. Work and Information by Otto Stutzer and E. A. Scheibe, 1924–1929. Volume III. Studies by Emil Grosse, 1927–1931. Volume IV. Studies made by the geologist of the Technical Section of the Department of Mines and Petroleum, E. Hubach, and information written by Fritz Bher, 1924–1933. Volume V. Information on the geological conditions of the valley of the Magdalena River, by E. Wiske, presented to the Government by the Julius Berger Konsortium Company, as part of the studies on the regulation of the river.

The present volume contains little of interest to the petroleum geologist, though several of the papers deal with coal deposits, and several deal somewhat with stratigraphy. Others are reports on deposits of emeralds, cinnabar, gold, and other minerals. The majority are short reports on the geology of various districts, including one rather long paper on the region above Antioquoia, in the valley of the Cauca River, between the Cordillera Central and Cordillera Occidental. The lack of an index map makes it difficult to determine the location of most of the areas covered.

The book contains several photographs, three in color, and many sketch maps and cross sections also in color, depicting the geological details described.

The bibliography of Colombian geology is very limited. According to Perry, the greatest amount of geological work done in the country is of a private nature, and not available for publication. It is his hope that the government will be able to carry on a systematic geological investigation, in order to learn something of the natural resources of the nation. He points out

the lack of adequate base and topographic maps, and hopes that through the aid of aerial photography, already in some use in the country, the preparation of such maps may be rapidly and economically expedited.

ROBERT H. DOTT

TULSA, OKLAHOMA
August 22, 1934

Petroleum Development and Technology, 1934. By the Petroleum Division. *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 107 (1934). 29 West 39th Street, New York. 465 pp. Cloth. 6.25×9.25 inches, outside. Price, $5.00.

Petroleum Development and Technology, 1934, contains papers and discussions presented before the Petroleum Division of the American Institute of Mining and Metallurgical Engineers at Los Angeles, September 29, 1933; at Dallas, October 6–7, 1933; and at New York, February 19–22, 1934.

Chapter I. "Production Engineering and Engineering Research."—Chapter I contains 10 papers: "Properties of Hydrocarbon Mixtures as Related to Production Problems"; "Theory and Practice of Direct Drilling"; "Instruments and Equipment for Recording Subsurface Pressures"; "Formation Testers"; "A Theoretical Analysis of Water-Flooding Networks"; "Recent Changes in Reservoir Pressure Conditions in the East Texas Field"; "Basic Data on Oil and Gas Wells"; "Effect of Gas Withdrawal upon Reservoir Fluids"; "A New Method for Measuring Vented Gas"; and "Comparative Resistance of Certain Commercial Ferrous Materials to Corrosion by Gaseous Hydrogen Sulphide."

The paper on reservoir pressures in East Texas, by G. L. Nye and C. E. Reistle, Jr., contains an interesting table and curve showing the withdrawal of oil and accompanying decrease in pressure, from October, 1932, to September, 1933. On October 25, 1932, the weighted average pressure of the field was 1,408 pounds per square inch, and the cumulative production at that date amounted to 206,158,300 barrels. On September 27, 1933, the pressure had dropped to 1,243 pounds, and the cumulative production amounted to 385,979,691 barrels, a total production of 119,821,391 barrels, with a decrease in pressure of 165 pounds. On the latter date, the rate of water encroachment was between 0.125 and 0.1 inch per day, and the author concluded that the slow encroachment of water had increased the recovery of oil from the sand that had been flooded.

Chapter II. "Petroleum Economics."—Chapter II contains 5 papers. The first, "An Aspect of the Arbitrary Restraint of Production," by John D. Gill, is highly provocative of thought, in raising several questions about the economic soundness of artificial restriction. Another, "Normal and Basic Prices of Crude Petroleum," by Norman D. Fitzgerald, presents a mathematical analysis of the elements which make up the price structure. Other papers in this group are: "Tanker Rates and Canal Tolls as Factors in Determining Markets of Foreign Oils"; "Seasonal Variations in Gasoline Consumption"; and "World Petroleum Consumption."

Chapter III. "Stabilization."—Chapter III contains 3 papers: "Stabilization in 1933"; "Kettleman Hills Middle Dome Unit Plan"; and "Efficient Utilization of Reservoir Energy."

Chapter IV. "Production."—Chapter IV is of great statistical value to anyone who deals with production and reserves, for it contains summary data

on number of wells, depths, producing formations, age, area, total production, and much other information, covering all the important fields in the oil-producing states of the United States and many foreign countries. These data have been accumulated under the direction of Frank A. Herald, and cover 277 pages of the book, with many tables.

Chapter V. "Refining."—Chapter V covers the developments in refinery engineering during 1933. The depressed conditions during the first 6–8 months of the year held back refinery modernization and expansion, but improvements during the latter part of the year stimulated new designing and construction. In the Appalachian district, a number of modern tube stills and fractionating towers replaced obsolete shell still units.

Manufacturers of gasoline have apparently settled on an octane rating of 70 as the maximum. In 1933 there was considerable agitation in agricultural sections for the blending of gasoline with alcohol, which necessitated extensive testing programs leading to a full understanding of the factors controlling the use of blended fuels. The proposals were found to be unsound from many standpoints.

ROBERT H. DOTT

TULSA, OKLAHOMA
September 1, 1934

RECENT PUBLICATIONS

BRAZIL

"Fisiografia e Geologia da Güiana Brasileira" (Physiography and Geology of Brazilian Guiana: Valley of Oiapoque and Region of Amapá), by Pedro Moura. *Geol. and Min. Survey of Brazil Bull. 65* (Rio de Janeiro, 1934). 109 pp., 90 photographs, 3 plates. 7.375×10.5 inches.

BURMA

"The Surveying of Deep Boreholes, with Special Reference to Some Work Recently Performed in Burma with the Martienssen Equipment," by W. E. Bruges. *Jour. Inst. Petrol. Tech.* (London), Vol. 20, No. 130 (August, 1934), pp. 749–90; 39 figs.

GENERAL

"Bibliography and Index of Geology Exclusive of North America. Vol. I—1933," by John M. Nickles and Robert B. Miller. *Geol. Soc. America Bibliographic Contributions* (1934). 405 pp. 6.375×9.625 inches.

"Die chemische Zersetzung der tierischen Substanz während der Einbettung in marine Sedimente" (Chemical Decomposition of Animal Substance during Deposition of Marine Sediments), by Fr. Hecht. *Kali verwandte Salze und Erdöl* (Berlin), Vol. 28, No. 17 (September 1, 1934), pp. 209–15; 1 map.

"Bibliographie des Sciences Géologiques" (Bibliography of Geological Sciences), by the Geological Society of France with the coöperation of the French Society of Mineralogy. 2d ser., Vol. IV (1933). 388 pp., listing 5,202 titles for the year 1933. 139 titles under bitumen, asphalt, oil, and gas. Outside dimensions, 6.5×10 inches. Société Géologique de France, 28, rue Serpente, Paris. Price, 50 francs.

World Petroleum Directory, 1934 edition. Compiled by N. R. Erard. "A yearly directory of the active oil companies of the world; a compact, authoritative, accurate book of reference giving the history, capital structure, personnel, location, and capacity of refineries and manufacturing plants; production capacity and location; marketing facilities and areas of distribution, etc.; in fact, all pertinent data pertaining to the world's oil companies." A general index of 50 blue pages covers all probable references. Listings are readily located by running heads at tops of pages. LII+578 pp. Outside dimensions, 8.75×11.5 inches. Cloth. Published by Russell Palmer, 56 West 45th Street, New York. Southwestern representative, Dudley W. Moore, Box 1821, Tulsa, Oklahoma. Price, $10.00.

Mineral Yearbook 1934, by the U. S. Bureau of Mines. 1,154 pp., 106 graphs. 72 chapters grouped under "Review of Mineral Industry;" "Metals;" "Nonmetals;" "Mine Safety." Cloth. Copies may be purchased from Supt. of Documents, Government Printing Office, Washington, D. C. $1.75.

The Mineral Industry During 1933, edited by G. A. Roush. Vol. 42 (1934). Covers statistics, technology, and trade for domestic and foreign fields. McGraw-Hill Book Company, New York. Cloth. Price, $12.00.

GEOPHYSICS

A Modern Outfit for Geophysical Prospecting. A Pamphlet of the American Askania Corporation, Houston, Texas, describing seismic reflection equipment. 11 pp., 9 figs. Contains selected list of references on seismic prospecting, with special reference to reflection shooting.

"Sur l'application des mesures de résistivité électrique du sous-sol aux problèmes stratigraphiques et tectoniques" (On the Application of Electric Resistivity Subsurface Measurements to Problems of Stratigraphy and Tectonics), by R. Pavans de Ceccatty. *Bull. Soc. Geol. France* (Paris), Ser. 5, Vol. 3, Nos. 1–2 (1933), pp. 29–43.

GERMANY

"Übersicht über das Vorkommen der Erdöle, Erdgase und Asphalte in Deutschland" (Review of Occurrences of Petroleum, Natural Gas, and Asphalt in Germany), by K. Fiege. *Kali, verwandte Salze und Erdöl* (Berlin), Vol. 28, No. 15 (August 1, 1934), pp. 183–91; 2 figs. First of a series.

POLAND

"Mines de pétrole et de gaz naturels en Pologne. Vol. II—Boryslaw. 1. Géologie" (Petroleum and Natural Gas in Poland. Vol. II. Boryslaw. 1. Geology), by K. Tolwinski. *Carpathian Geol. Survey Bull. 22* (Boryslaw, Poland, 1934). 159 pp., 41 figs., 4 folded maps, 1 folded stratigraphic section. In Polish and French. Paper. 6.25×9.5 inches.

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THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

The United States Geological Survey has had a field party in Crawford, Cherokee, and Labette counties, Kansas, during the past summer, studying the geology and coal resources of the area. W. G. PIERCE was in charge of the party, including FRED HAASE, C. E. STRAUB, W. H. COURTIER, EDWARD KOESTER, E. GRIFFIN, L. M. WILSHIRE, and FRED COLEMAN.

G. W. NOBLE has returned to Massachusetts Institute of Technology to continue studies in statistical and economic analysis as applied to the petroleum industry.

E. G. LEONARDON, Schlumberger Electrical Prospecting, Houston, Texas, presented a paper before the Oklahoma City Geological Society, September 10, entitled "An Electrical Method of Surveying Bore Holes."

FREDERICK G. CLAPP has returned to his New York office after spending the first eight months of the year in studies of conditions in several countries of western Asia.

WERNER TAPPOLET, geologist with the Royal Dutch Shell, is again engaged in exploratory work in Mexico, after a furlough in Switzerland. Letters may be addressed to C. M. P.-El Aguila, Apartado postal 150, Tampico, Tamps., Mexico.

C. W. SANDERS, formerly district geologist for the Shell Petroleum Corporation at Amarillo, has been transferred to the company's division office at Houston, Texas.

G. ALLEN WILLIAMS, geologist, Livingston, Texas, has changed his address to 2237 Quenby Road, Houston, Texas.

ERNEST K. PARKS, production engineer, Standard Oil Company of California, has been transferred from Taft to Los Angeles, California. Mail may be addressed to Box 1390, Station C.

LUTHER B. SMITH, JR., geologist with the Arkansas Natural Gas Corporation, has been transferred from Tyler, Texas, to Waynesboro, Mississippi.

H. F. MOSES has resigned as petroleum adviser to the Turkish Government, Ankara, Turkey, and may be addressed at 7350 Indiana Avenue, Chicago, Illinois.

J. P. MCCULLOCH has changed his permanent mailing address from Princeton, New Jersey, to No. 7, Place Vendome, Paris (1°), France.

H. V. HOWE, head of the geological department of the Louisiana State

University at Baton Rouge, and M. A. HANNA, paleontologist with the Gulf Production Company at Houston, Texas, have prepared discussions of Gulf Coast sediments, particularly the correlation of the *Heterostegina* zone as developed in the core record of a deep well in southern Mississippi with surface outcrops. These articles, with a map, cross section, and faunal charts, are included in the guide book of the eleventh annual field trip of the Shreveport Geological Society which was held in Mississippi, October 5 and 6. The book sells for $5.00 per copy. G. D. Thomas, Shell Petroleum Corporation, Shreveport, Louisiana, is secretary-treasurer of the society.

W. J. MEAD, formerly professor of geology at the University of Wisconsin, has been appointed head of the department of geology at Massachusetts Institute of Technology, succeeding WALDEMAR LINDGREN, retired.

DORSEY HAGER, consulting geologist and petroleum engineer, has opened a consulting office at 918 Chrysler Building, New York City. In the *Oil Weekly* of September 3 he had an article entitled, "New Supplies and Reserves to Meet Consumption Demands Must Be Found." It is illustrated by a table showing total oil production to date by states, and a map showing location of producing oil and gas fields and areas of possible oil and gas production in the United States.

T. A. BENDRAT has moved from Montgomery, Alabama, to 21 Calloway Street, Beckley, West Virginia, where he is connected with the geological department of Beckley College.

The San Antonio Geological Society saw the United States Bureau of Mines film "The Evolution of the Oil Industry," after dinner, at 7:30 P.M., at the Petroleum Club, September 10.

W. F. KNODE, chief petroleum engineer of the Texas Railroad Commission, has resigned that position to open a consulting office at Corpus Christi, Texas.

W. KEITH MILLER is employed in the geological department of the Carter Oil Company, Tulsa, Oklahoma.

W. ROSS KEYTE is in charge of the Wichita Falls, Texas, office of Dowell, Inc.

W. ARMSTRONG PRICE, consulting geologist of Corpus Christi, Texas, addressed the Houston Geological Society, August 30, on "The Corpus Christi Structural Basin."

DAVID WHITE, who has been with the United States Geological Survey 48 years, was awarded the Sir Boverton Redwood medal for distinguished service at the summer meeting of the Institute of Petroleum Technologists at London.

J. A. HOEKSTRA, of the De Bataafsche Petroleum Maatschappij, Royal Dutch Shell subsidiary, has returned to Batavia, Dutch East Indies.

E. H. FINCH, recently of San Antonio, Texas, may now be addressed in care of the Venezuelan Petroleum Company, Apartado 1706, Caracas, Venezuela.

The American Petroleum Institute will hold its fifteenth annual meeting, on November 12–15, at the Baker and Adolphus hotels, Dallas, Texas.

The Fourth Topographic and Geologic Survey of Pennsylvania, GEORGE H. ASHLEY, State geologist, celebrated its fifteenth anniversary on September 1. It has issued an 8-page illustrated pamphlet, *Fifteen Years*, outlining some of its service to the State. The Survey employs 14 geologists, 8 full time, and 6 part time, and coöperates with 6 geologists of the United States Geological Survey. Pennsylvania has maintained geological surveys, though not continuously, for nearly 100 years.

CARROLL H. WEGEMANN is spending some months in Germany as consulting geologist for the Wintershall Aktiengesellschaft, Hohenzollernstrasse 139, Kassel. His wife and daughter have accompanied him.

The name of the Mid-Kansas Oil and Gas Company was changed to the Marathon Oil Company, last August, at which time FRANK R. CLARK, past-president of the A.A.P.G., and chief geologist of the company, was elected a director of the Marathon Oil Company.

The sixth annual meeting and field trip of the San Antonio Section of the Association will be held on November 2–5. On Friday, November 2, the field trip, commencing at Campbellton, will cover parts of Atascosa, Live Oak, McMullen, Duval, and Webb counties, including the Tertiary section and the Jacob, Calliham, Eagle Hill, Government Wells, Saranosa, and Cole fields, and ending at Laredo for the night. On November 3, the technical program at Laredo will probably include the following papers: "Relationship of Vicksburg Group to Formations Which Overlie It in Mississippi," by H. V. HOWE; a symposium on the "Government Wells Field," including a "Study of Subsurface Conditions," by J. B. WHISENANT and JACK TRENCHARD, and a discussion of "Bottom Hole-Pressure Survey," by E. C. RACH; "Geology of Tertiary of Northeastern Mexico," by J. LAIRD WARNER; "The Claiborne Section," by W. F. CALOHAN and FRITH OWEN; and "Corpus Christi Structural Basin," by W. ARMSTRONG PRICE. On November 4 and 5, a trip through the Tertiary and Cretaceous sections of northeastern Mexico will commence at Nuevo Laredo and end at Monterrey. All arrangements will be made for tourist passports and entry of automobiles into Mexico. A program is being arranged for the ladies although there will be no accommodations for them on the first night of the Mexico trip. It is planned that they shall rejoin the trip at Monterrey.

S. MORSE WILLIS has changed his address from 510 North Kentucky Avenue, Roswell, New Mexico, to 500 North Seventh Street, Ponca City, Oklahoma.

J. DAVID HEDLEY, geologist with the Barnsdall Oil Company, has changed his address from Thibodaux, Louisiana, to 2212 Esperson Building, Houston, Texas.

CHESTER D. WHORTON and H. ROGERS VAN GILDER, consulting geologists, of Coudersport, Pennsylvania, have dissolved their partnership. Van Gilder has accepted a position with the North Branch Development Com-

pany, at Wellsboro, Pennsylvania, and Whorton will maintain his consulting office in Coudersport.

T. J. ETHERINGTON, geologist with the Standard Oil Company of California, and formerly at Barranquilla, Colombia, S. A., may now be addressed in care of Bin XX, Taft, California.

On Wednesday noon, November 14, the American Petroleum Institute will be host at a complimentary luncheon to the geologists of the industry who attend the convention to be held in Dallas. This luncheon will be so arranged that it will not conflict with other similar meetings. Both geologists and petroleum engineers are cordially invited to attend the luncheon. Those who expect to be at the convention are requested to notify LEON J. PEPPERBERG, chairman of the Geologists Committee, 1311 Magnolia Building, Dallas, Texas, in order that proper seating arrangements may be made.

The annual meeting of the Pacific Section of the Association will be held at the Mayfair Hotel, Los Angeles, on November 8 and 9. The technical session will be held from 9 A.M. to 12 A.M. and from 2 P.M. to 4 P.M. There will be an informal luncheon Thursday and Friday noon, a dinner-dance Friday evening, and a paleontological meeting Thursday evening. A. A. CURTICE, 435 A. G. Bartlett Building is president, and W. D. RANKIN, 1121 Subway Terminal Building, is secretary-treasurer of the Section.

ROBERT J. RIGGS, chief geologist of the Indian Territory Illuminating Oil Company, Bartlesville, Oklahoma, resigned October 15, to become consulting geologist for the Stanolind Oil and Gas Company, at Tulsa.

W. H. WHITTIER, formerly at Albuquerque, New Mexico, may now be addressed at Box 1223, Salt Lake City, Utah.

JACK M. COPASS has changed his address from Norman, Oklahoma, to Box 896, Shawnee, Oklahoma.

D. HAROLD CARDWELL, geologist with the Sun Oil Company, Dallas, Texas, is now at Huntsville, Texas, and may be addressed at Box 449.

D. G. BARNETT, geologist with the United Production Corporation, has been transferred from Houston to Beeville, Texas.

EDGAR D. KLINGER has changed his address from the Federal Building, Coleman, Texas, to 502 South Adams Street, San Angelo, Texas.

SELDEN R. SELF, geologist with the Amerada Petroleum Corporation, has been transferred from San Angelo to Midland, Texas.